A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL

R. Bernstein
FNAL

Collaboration

57 physicists,
14 institutions

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Experiment's 1st Stage is MECO adapted to FNAL

many MECO collaborators with vital knowledge

Outline

- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e

What is μe Conversion?

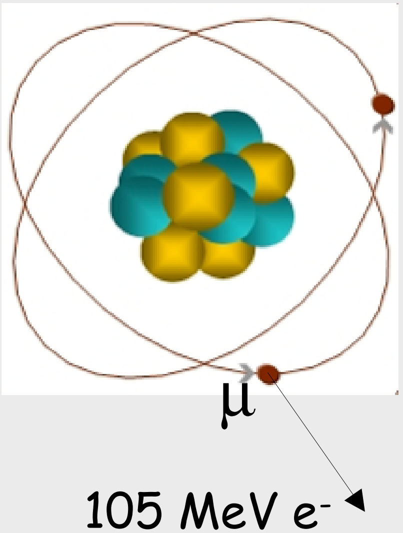
muon converts to electron in the presence of a nucleus

$$\mu^- N \to e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z)\,)}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)\,)}$$

- Charged Lepton Flavor Violation (CLFV)
- Related Processes:

μ or $\tau \to e\gamma, e^+e^-e$, $K_L \to \mu e$, and more



"Who ordered that?"

– I.I. Rabi, 1936

After the μ was discovered, it was logical to think the μ is just an excited electron:

- expect BR($\mu \rightarrow e\gamma$) ≈ 10^{-4}
- Unless another ν, in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)

➡ same as GIM mechanism!

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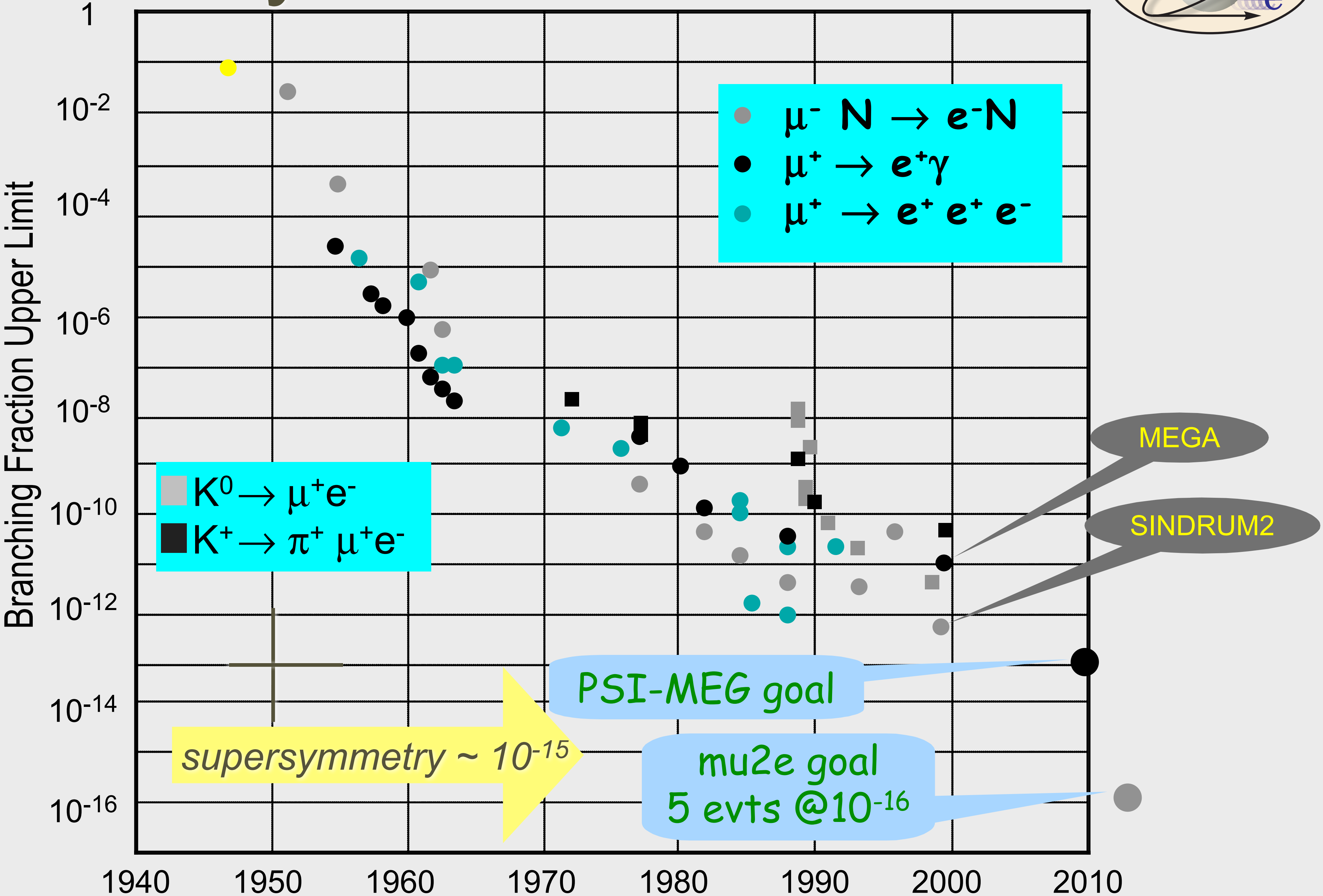
[1] Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$.

History of CLFV Searches



Endorsed in US Roadmap

FNAL has proposed muon-electron conversion as a flagship program for the next decade

Strongly endorsed by P5:

"The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. Development of a muon-to-electron conversion experiment should be strongly encouraged in all budget scenarios considered by the panel."

Mu2e is a central part of the intensity frontier program

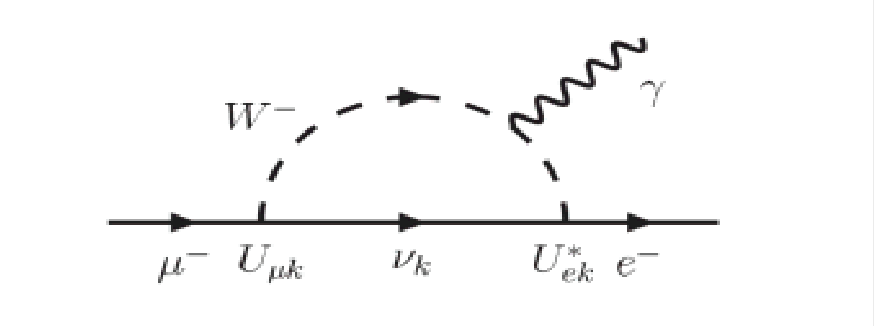
Current and Planned Lepton Flavor Violation Searches

- Neutrino Oscillations!
- τ LFV current limits at 10^{-7} for $\tau \rightarrow \mu\gamma$
- MEG and $\mu \rightarrow e\gamma$
- Mu2e:
  - Strengths of muon-electron conversion
  - Complementarity to other processes

Neutrino Oscillations and Muon-Electron Conversion

- ν's have mass! *individual lepton numbers are not conserved*

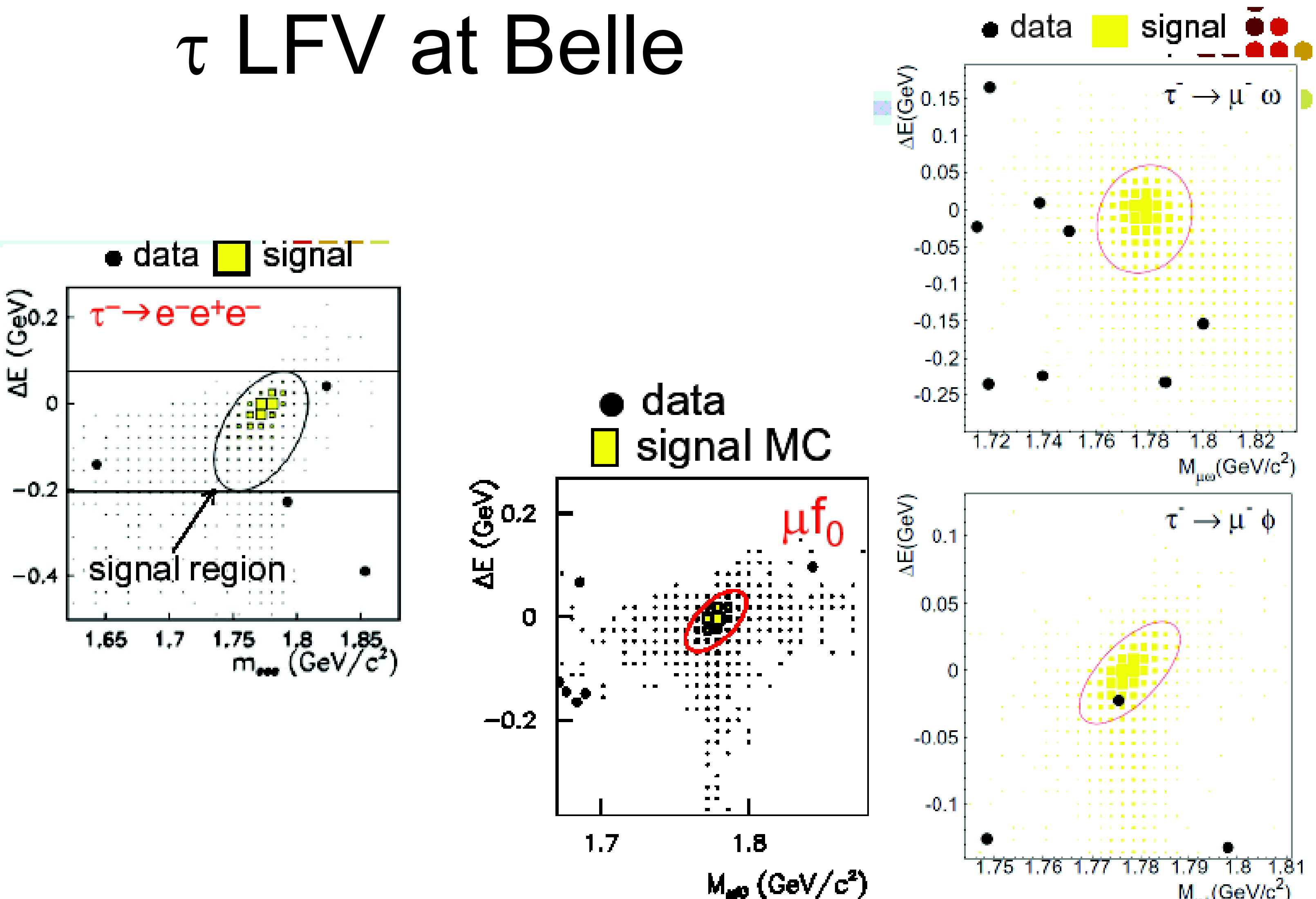
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well



$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$ ☹

Lepton Flavor Violation

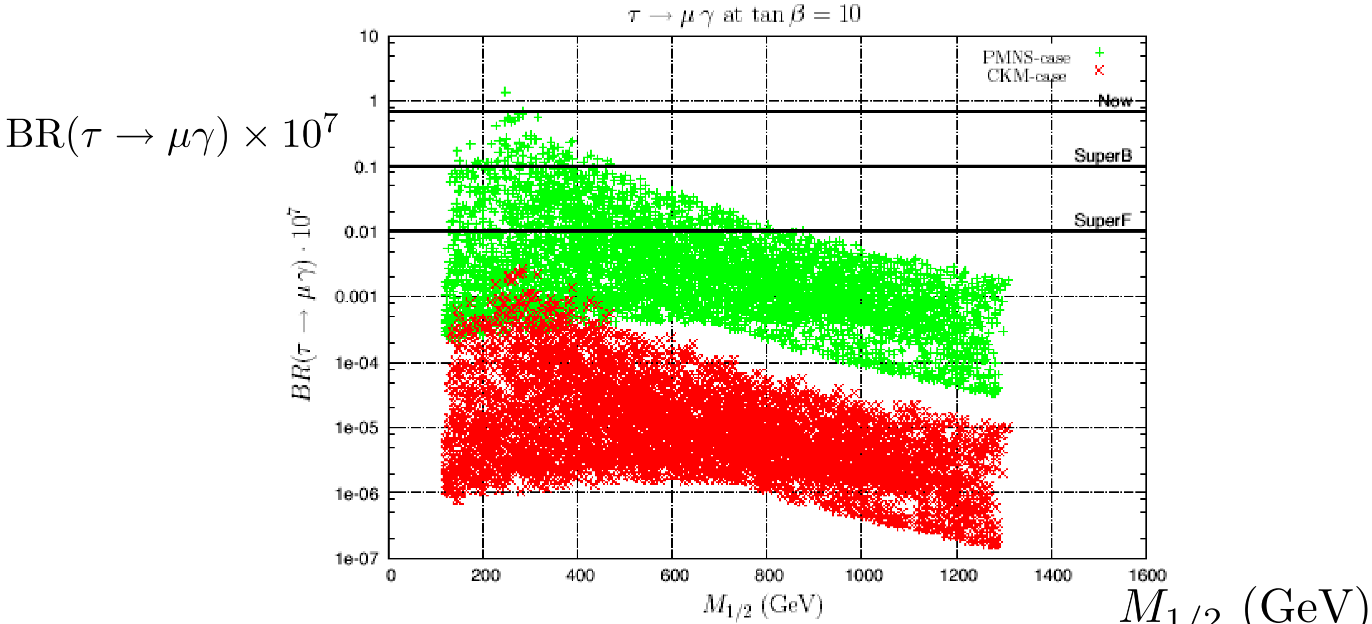
τ LFV at Belle



Supersymmetry in Tau LFV

L. Calibbi, A. Faccia, A. Masiero, S. Vempati hep-ph/0605139

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)



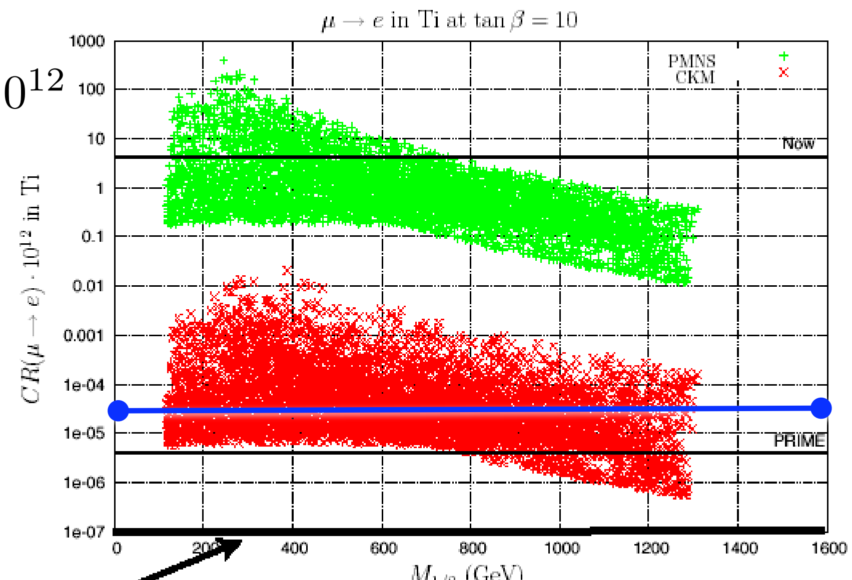
L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

neutrino mass via the see--saw mechanism, analysis is performed in an SO(10) framework

And Muon-Electron Conversion

Neutrino-Matrix Like (PMNS)   Minimal Flavor Violation(CKM)

$\mathrm{BR}(\mu \to e) \times 10^{12}$



Mu2e Phase I

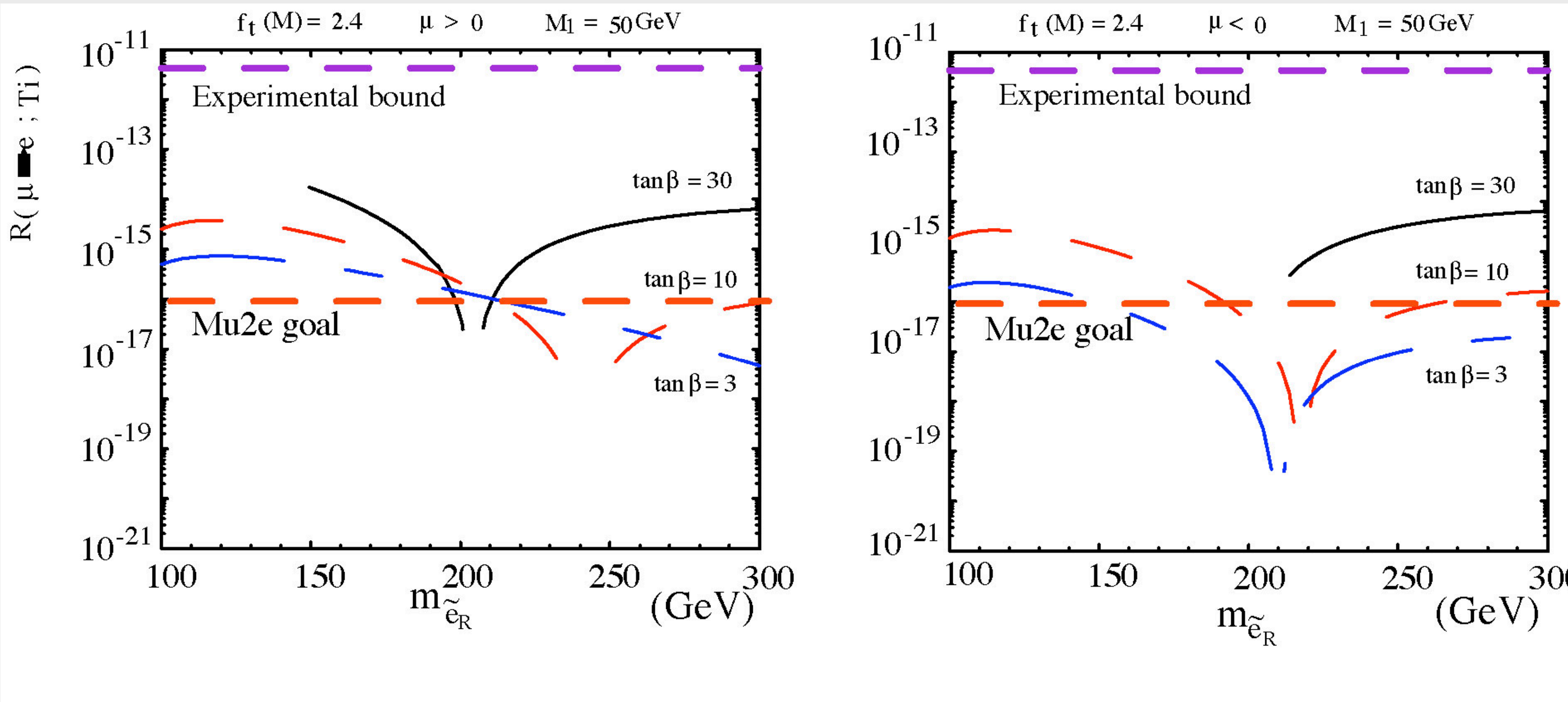
Project X reach

$M_{1/2}$ (GeV)

L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

complementarity between Lepton Flavor Violation (LFV) and LHC experiments!

Supersymmetry and Mu2e in Minimal SU(5)

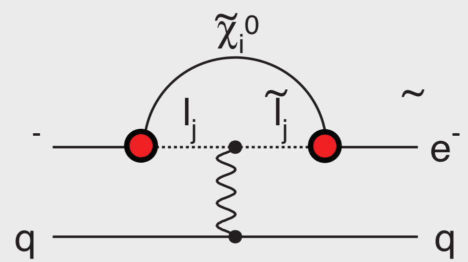


J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B 391, 341 (1997). [Erratum-ibid. B397, 357 (1997).]

Contributions to μe Conversion

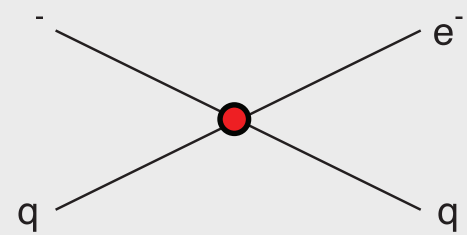
Supersymmetry

rate ~ 10^{-15}



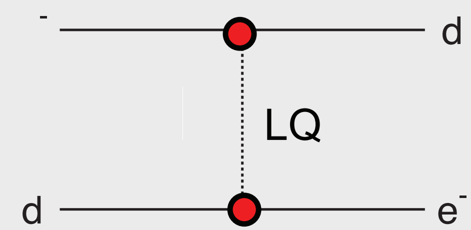
Compositeness

$\Lambda_c \sim 3000$ TeV



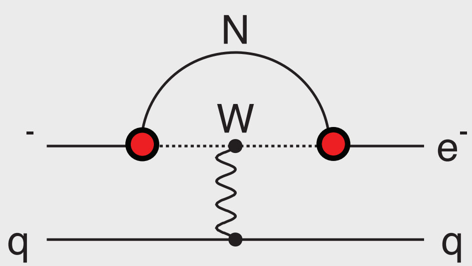
Leptoquark

$M_{LQ} =$
$3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



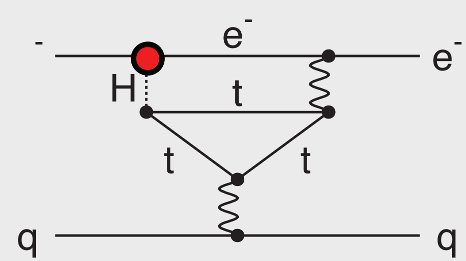
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\times10^{-13}$



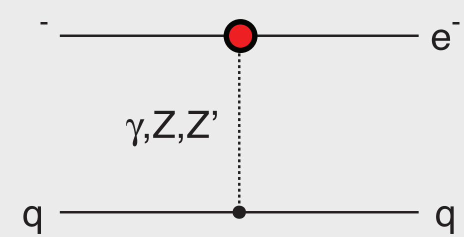
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Heavy Z' Anomal. Z Coupling

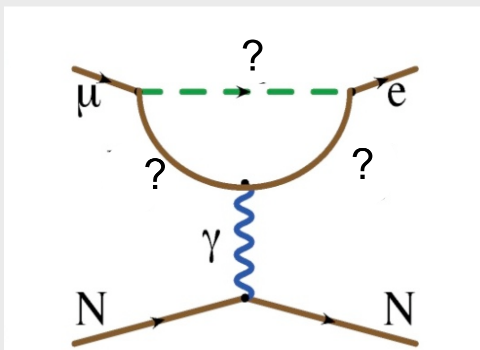
$M_{Z'} = 3000$ TeV/c^2



“Model-Independent” Picture

$$L_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

“Loops”

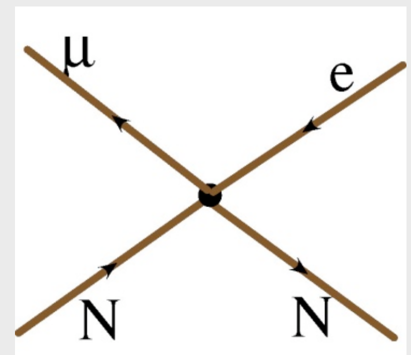


κ

Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ

“Contact Terms”



Λ

Exchange of a new, massive particle

Does not produce μ→eγ

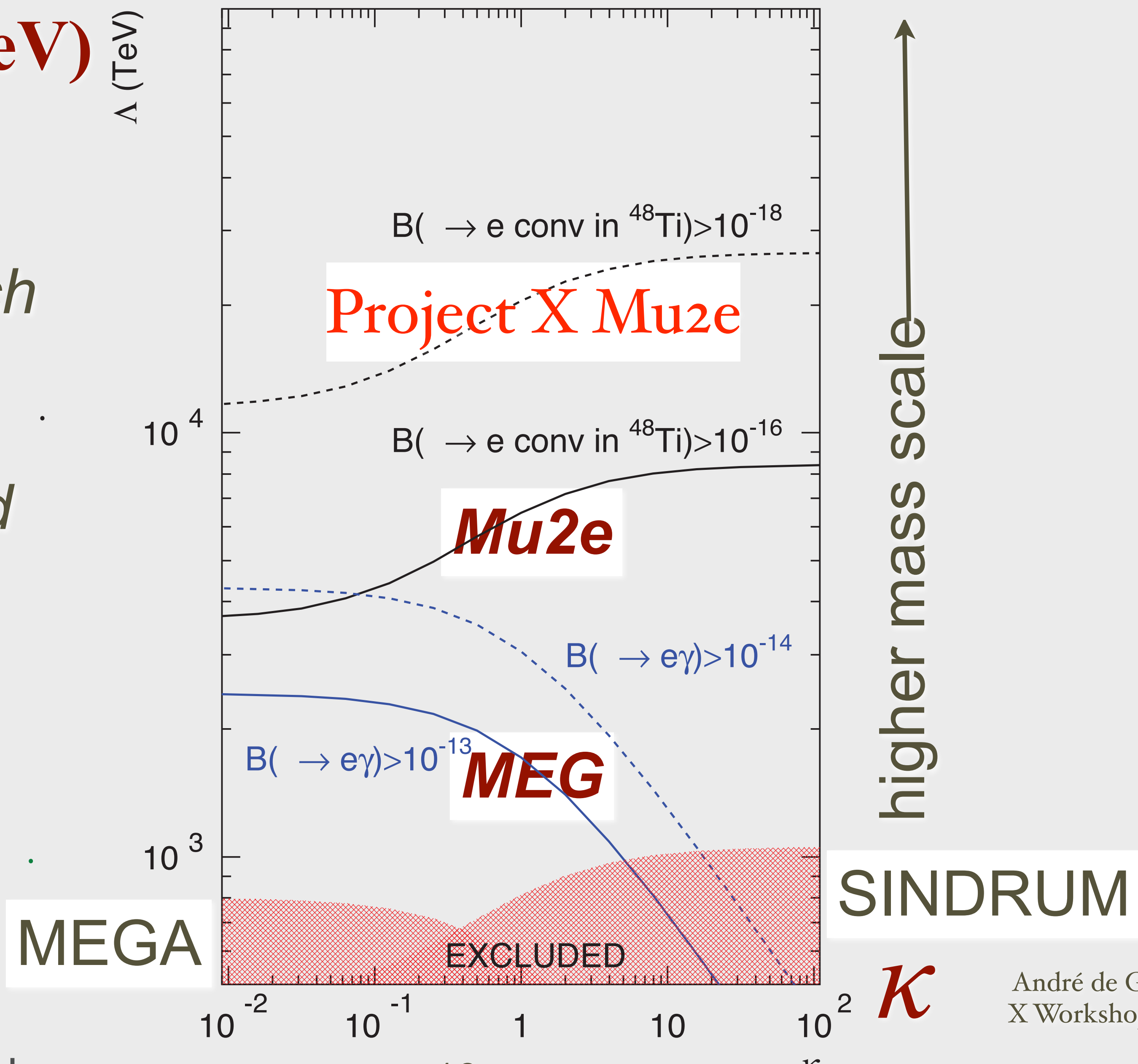
Quantitative Comparison?

μe Conversion and μ→eγ

Λ (TeV)

1) *Mass Reach to 10^4 TeV*

2) *x10 beyond MEG in loop-dominated physics*



André de Gouvêa, Project X Workshop Golden Book

Outline

- The search for muon-electron conversion
- *Experimental Technique*
- Fermilab Accelerator
- Project X Upgrades and Mu2e

Overview Of Processes

μ^- stops in thin Al foil

μ^- in 1s state

Al Nucleus
~4 fm

the Bohr radius is ~ 10 fm,
so the μ^- sees the nucleus

total disappearance rate =0.864 μ sec

60% captured

1.4 μ sec

1. μ^- emits ν
2. Al turns into Mg

NORMALIZATION

40% decay-in-orbit

2.2 μ sec

decays by normal process but can recoil off nucleus

BACKGROUND

Why Normalize to Capture?

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

Al turns into Mg

- Nuclear wavefunctions “cancel,” calculation simpler

- As muon cascades to 1s, X-rays give stop rate

1. μ^- emits ν
2. Al turns into Mg

- and Mg $\rightarrow$Al yields a 2.6 MeV β followed by γ that can be used to measure capture rate

NORMALIZATION

Two Classes of Backgrounds

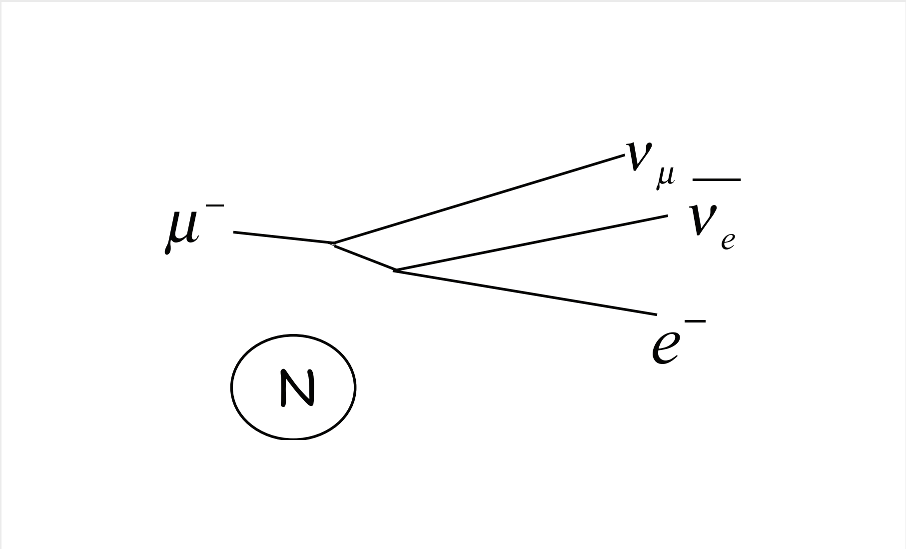
	Prompt	Decay-In-Orbit
Source	Mostly π's produced in target	Physics Background nearly indistinguishable from signal
Solution	Design of Muon Beam, formation, transport, and time structure	Spectrometer Design: resolution and pattern recognition

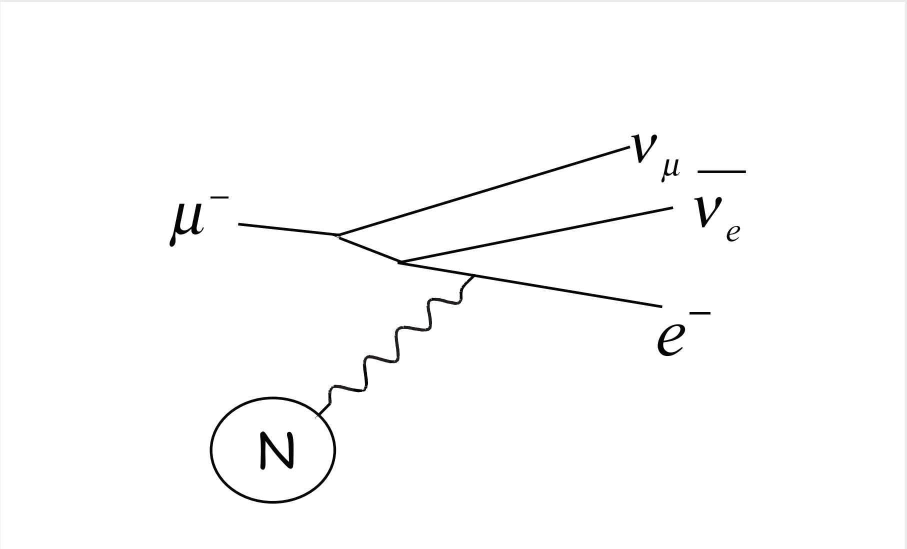
Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector region: π, neutrons, pbars

- Radiative pion capture, π-+A(N,Z)->γ +X. $\pi^- \mathrm{Al} \rightarrow \gamma\ \mathrm{Mg}$
  - γ up to m_π; $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal. Major limitation in best existing experiment, SINDRUM II.
- Beam electrons: incident on the stopping target and scatter into the detector region. Need to suppress e^- with E>100 MeV near signal
- In-flight muon decays yielding electrons: if they decay with momentum > 76 MeV/c, can yield electron in signal region

Decay-in-Orbit Background





- High Rate
- Peak 52.8 MeV
- Detector insensitive to these

- *Zero energy neutrinos and coherent scatter off nucleus put DIO's at conversion energy*
- Rate falls as $(E_{max} - E)^5$
- Fraction within 2 MeV of signal is 1.2×10^{-15}

Design of Mu2e

Examine previous best experiment

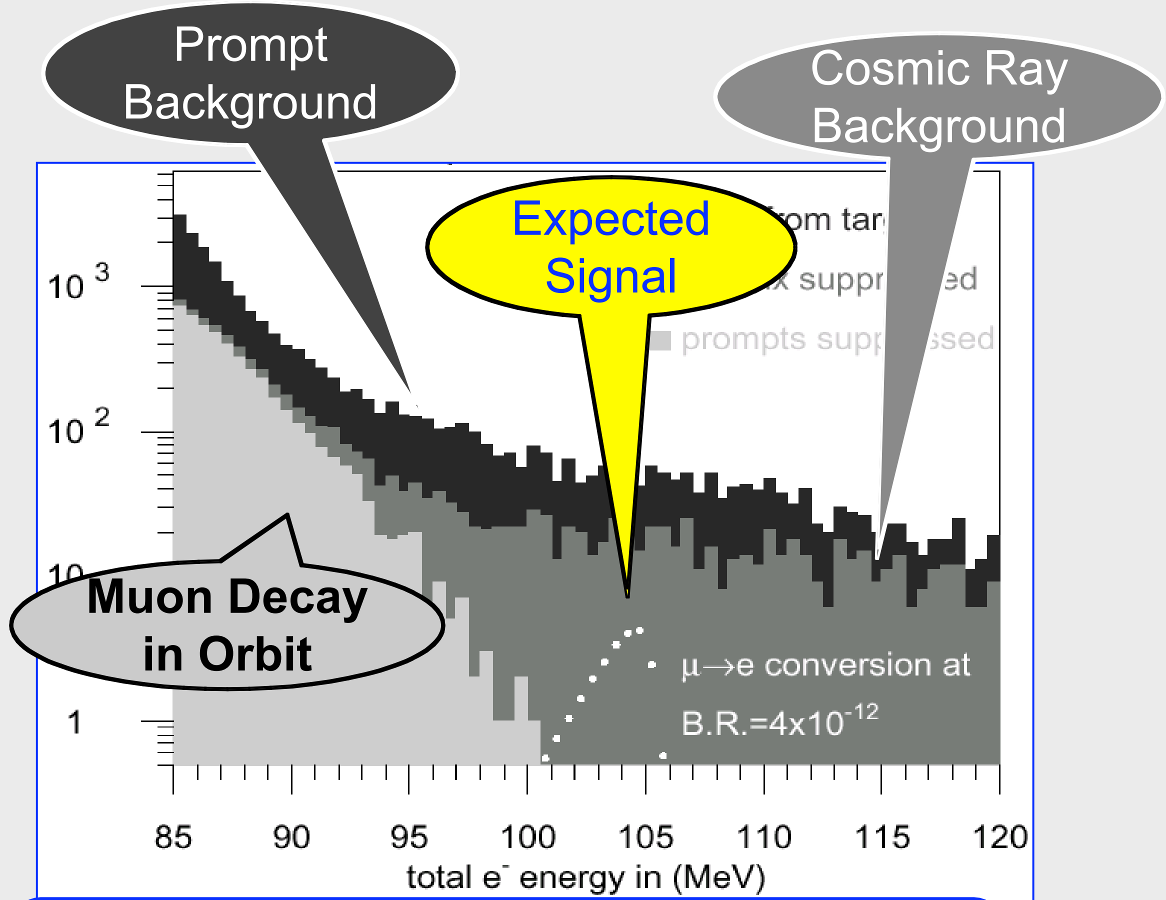
- What were the limitations?
  - limitations from prompts
  - limitations from Decay-in-Orbit

How can we do better?

Previous Best Experiment

SINDRUM-II

- $R_{\mu e} < 6.1 \times 10^{-13}$ in Au
- Want to probe to 10^{-16} or better
- $\approx 10^4$ improvement

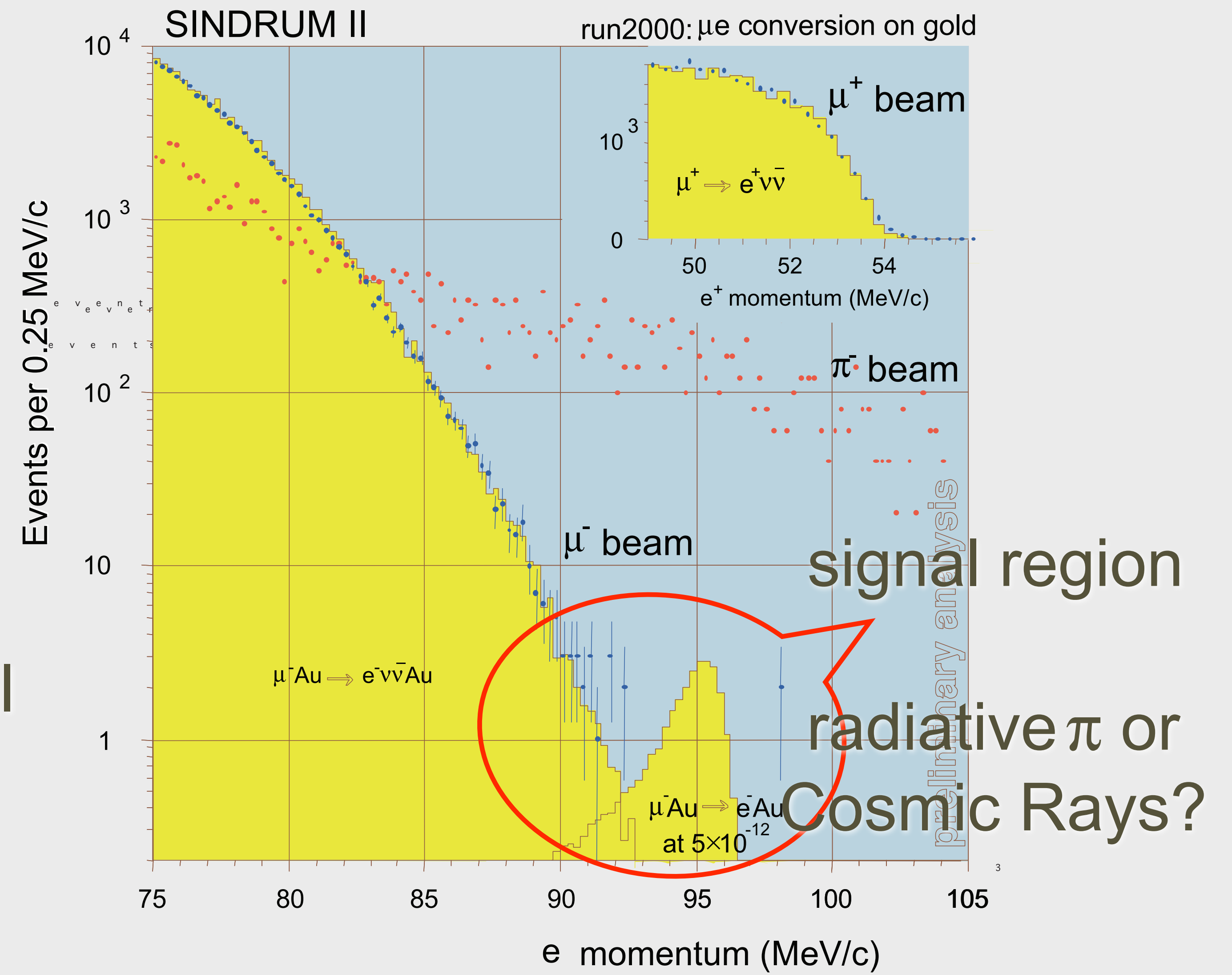


Experimental signature is 105 MeV e⁻ originating in a thin Ti stopping target

SINDRUM II Results

- Final SINDRUM-II on Au

- Note Two Background Events past Signal Region



W. Bertl et al, Eur. Phys. J. C **47**, 337-346 (2006)

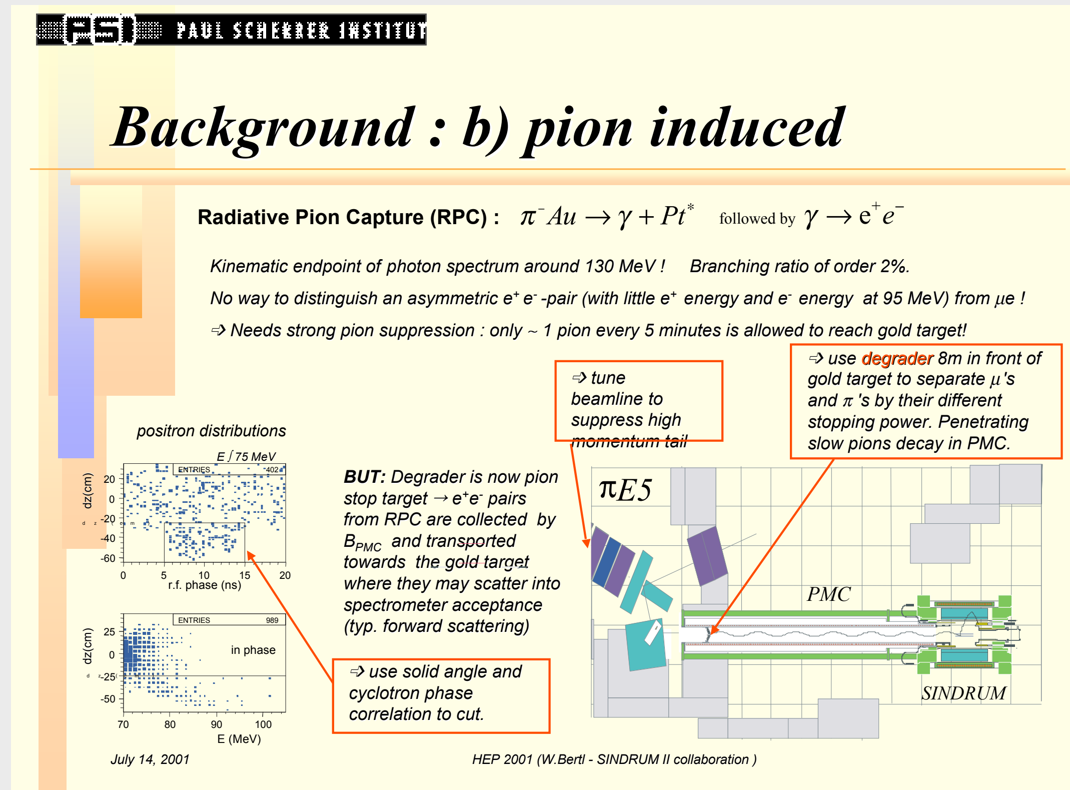
July 14, 2001 *HEP 2001 (W.Bertl - SINDRUM II collaboration)*

What Limited SINDRUM-II?

DC Beam

no time separation between signal and prompt background

radiative π capture



How Can We Do Better?

$>10^3$ increase in muon intensity from SINDRUM

Requiring

Pulsed Beam to Eliminate prompt backgrounds

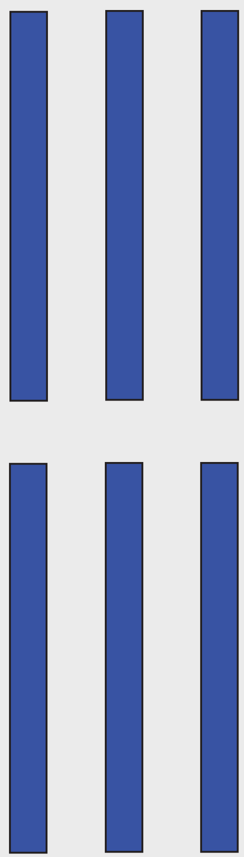
protons out of beam pulse/ protons in beam-pulse $< 10^{-9}$
and we must measure it

Removal of Line-of-Sight

requires curved solenoid transport line

Advantage of Pulsed Beam

target foils: muon converts here



Recall:
Muon-electron conversion signal is a

single,monoenergetic electron

pulsed beam lets us wait until after prompt backgrounds disappear

Advantage of Pulsed Beam

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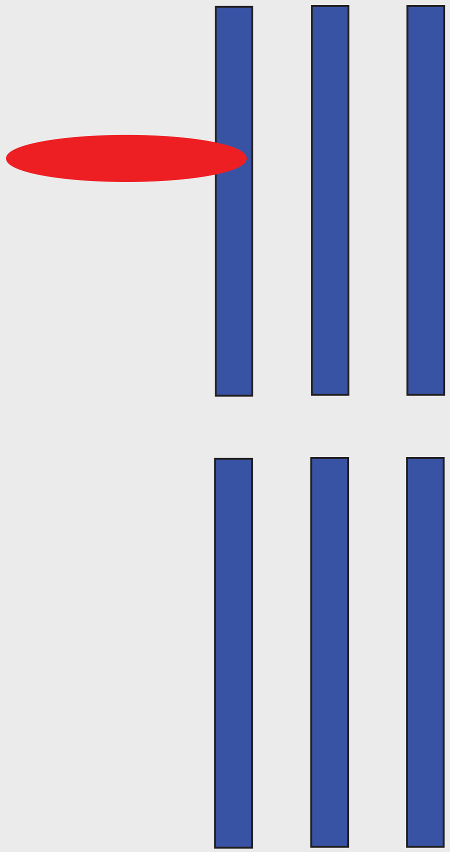

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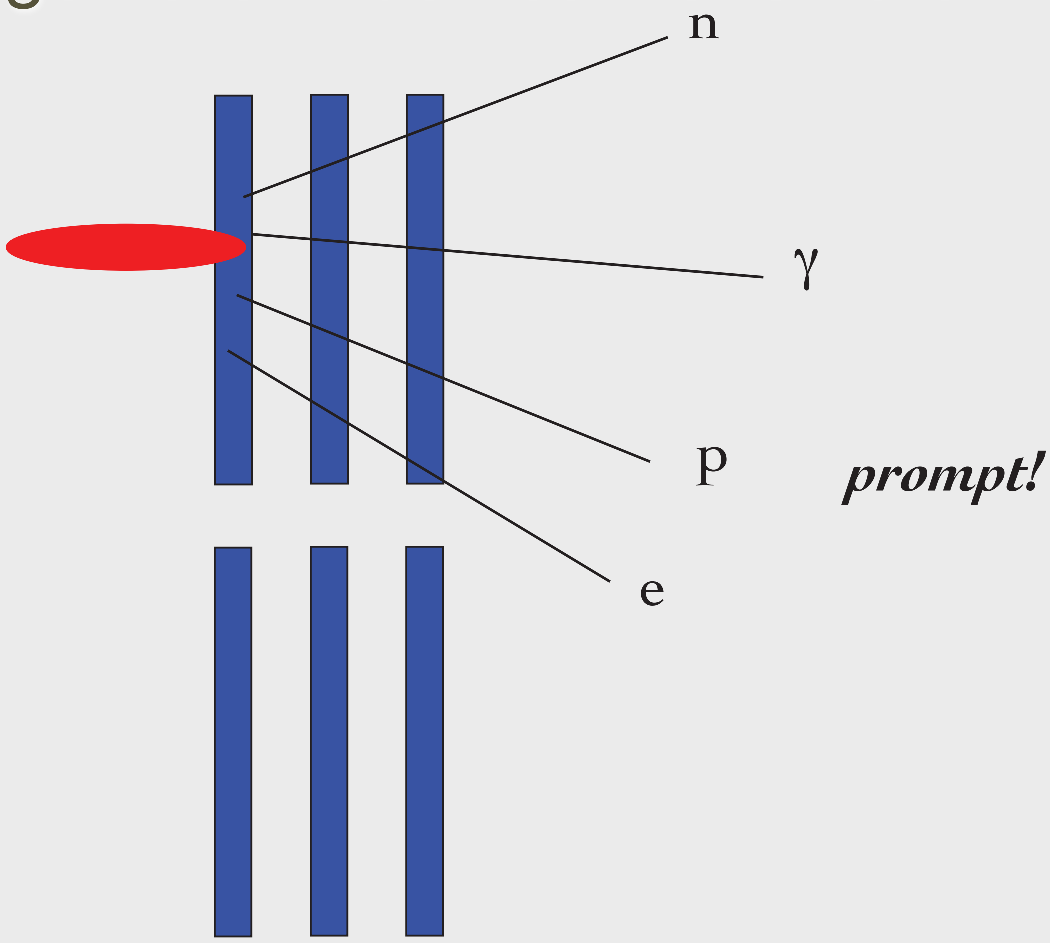

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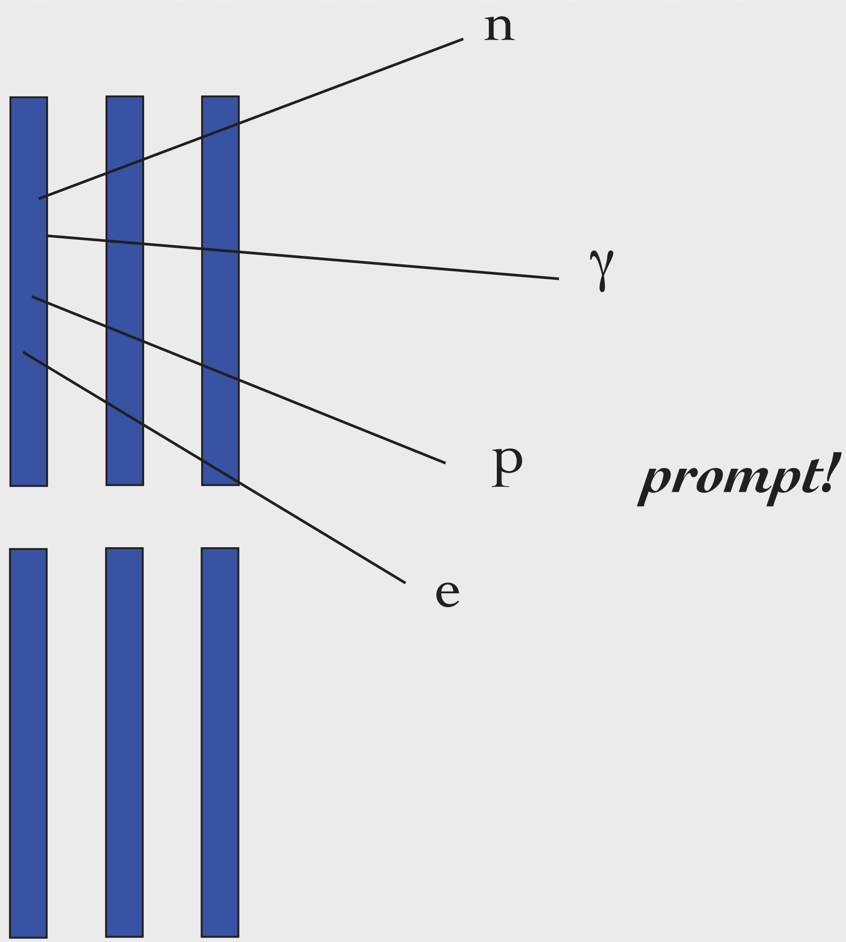

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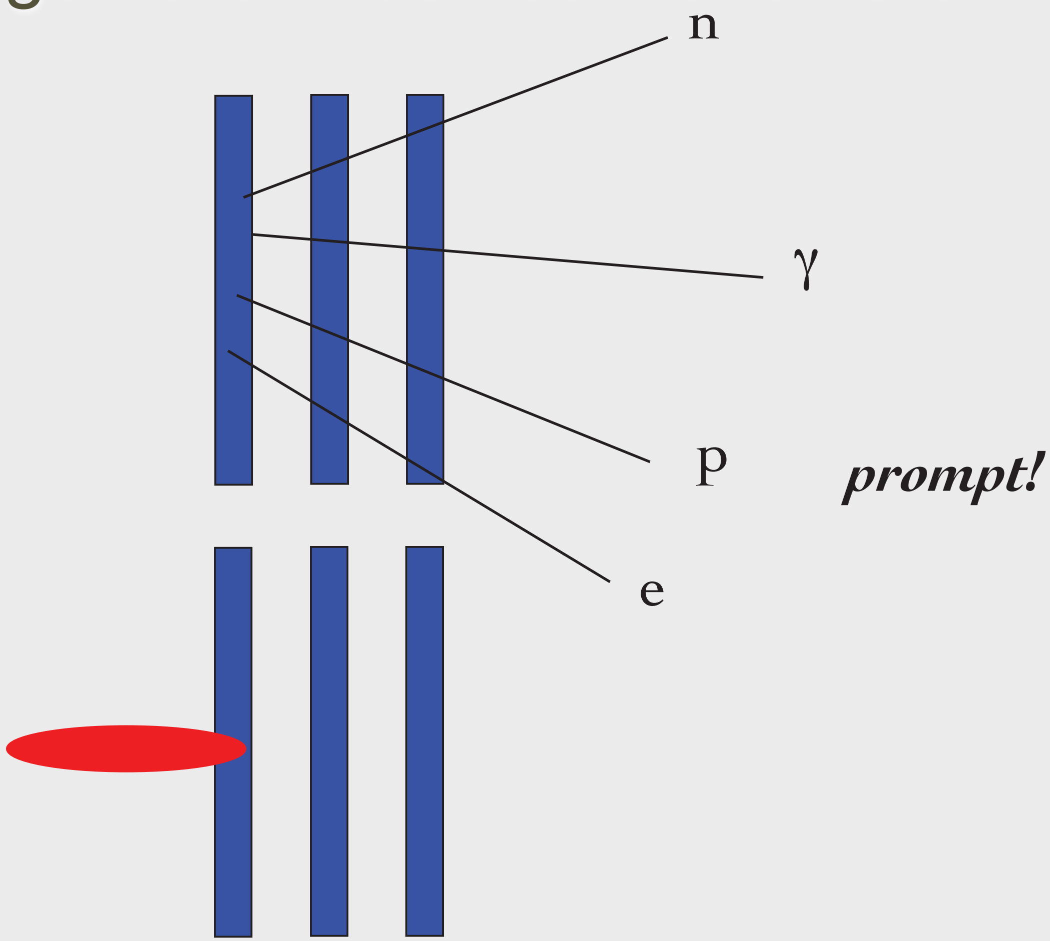

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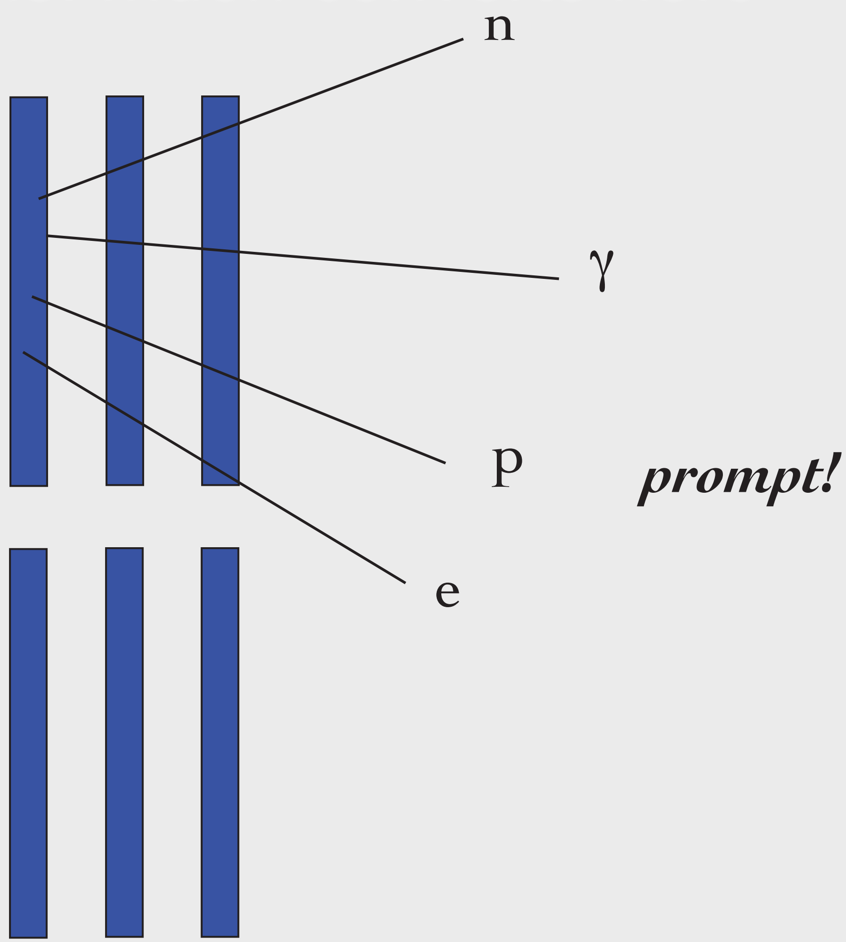

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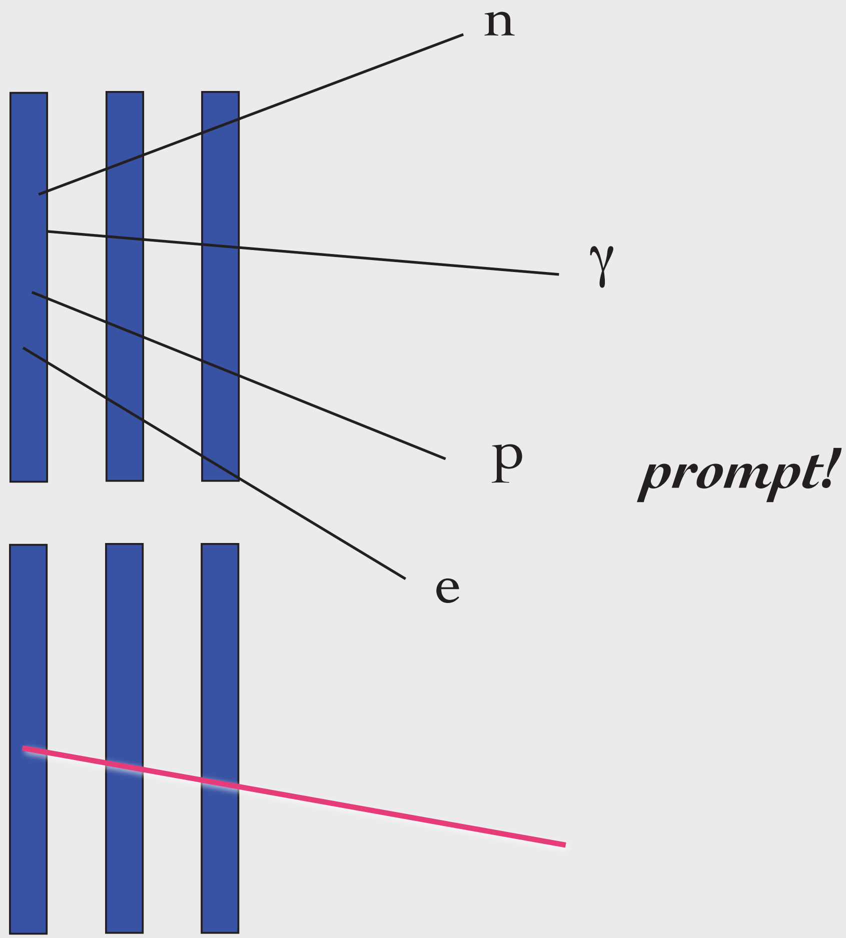


delayed 105 MeV electron

Recall:
Muon-electron conversion signal is a

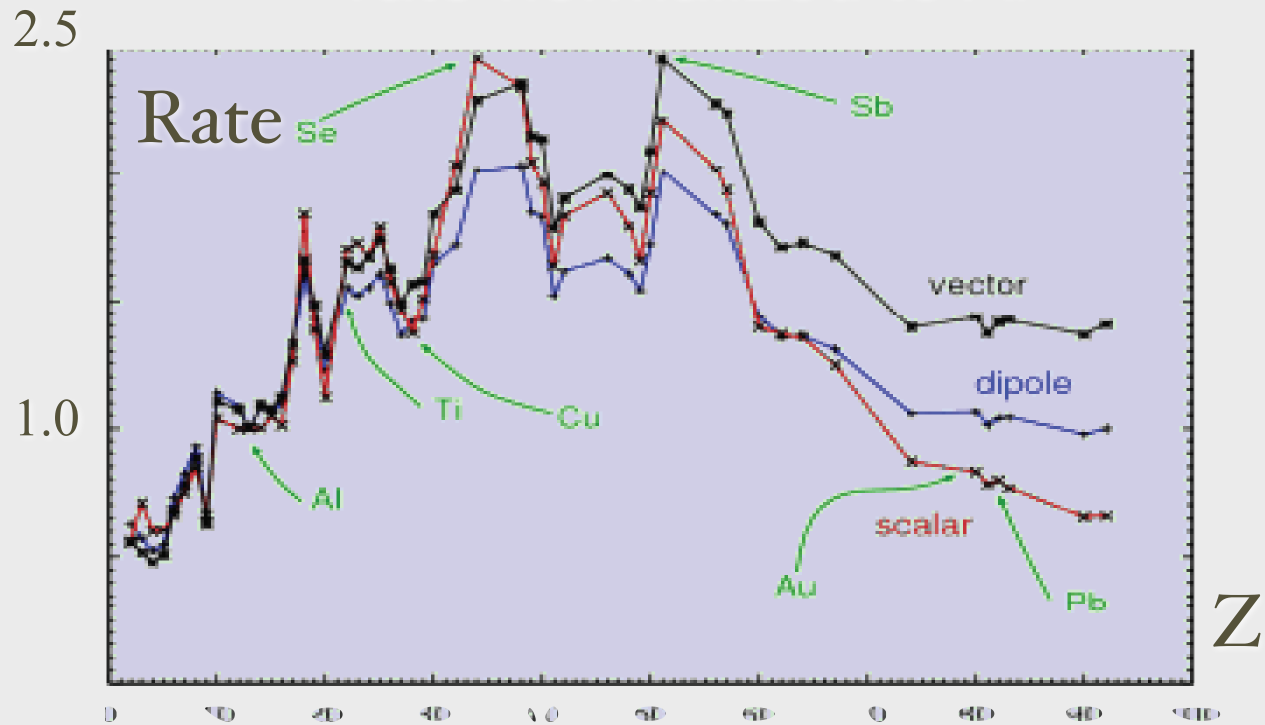
single,monoenergetic electron

pulsed beam lets us wait until after prompt backgrounds disappear

Choice of Stopping Material: rate vs wait

- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics
- Why start with Al?

rate normalized to Al



Kitano, et al., PRD 66, 096002 (2002)

shape governed by relative conversion/capture rate, form factors, ...

Prompt Background and Choice of Z

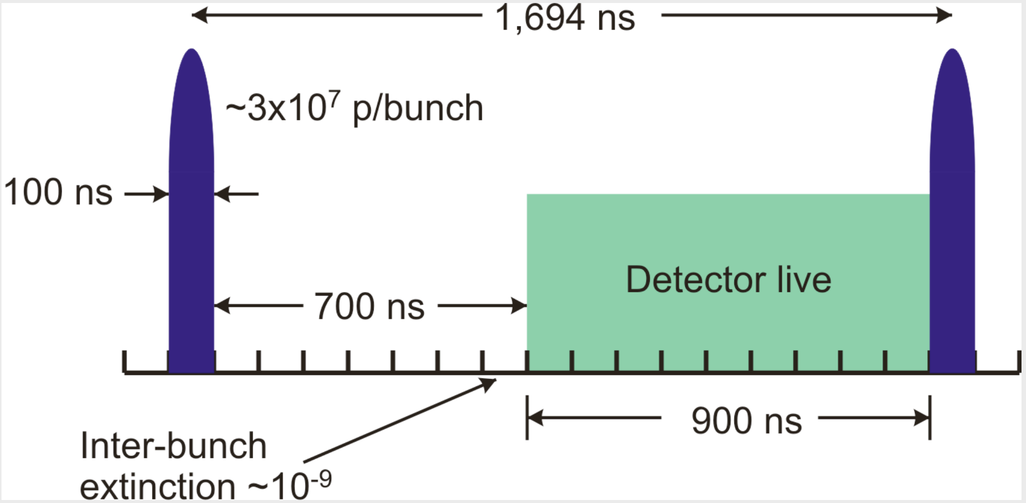
choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds

Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au (79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible

Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_μ, pulse separation ≈ τ_μ
  - FNAL Accumulator has circumference 1.7μsec !
- Extinction between pulses < 10^{-9} needed

  = # protons out of pulse/# protons in pulse

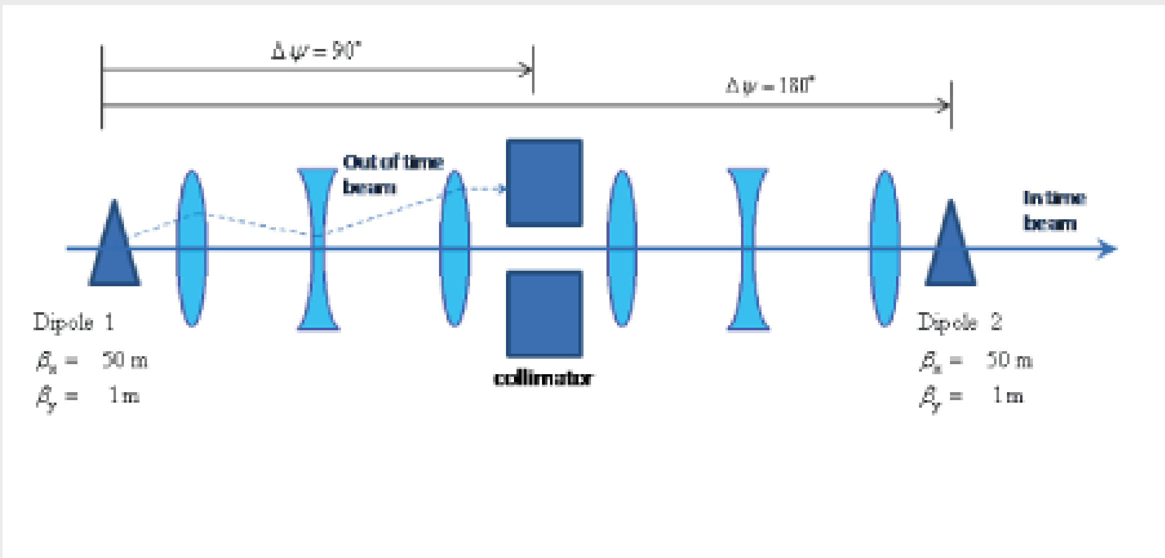


- 10^{-9} based on simulation of prompt backgrounds

Extinction Scheme

achieving 10^{-9} is hard; normally get $10^{-(2\text{-}3)}$

- Eliminate protons in beam in-between pulses:

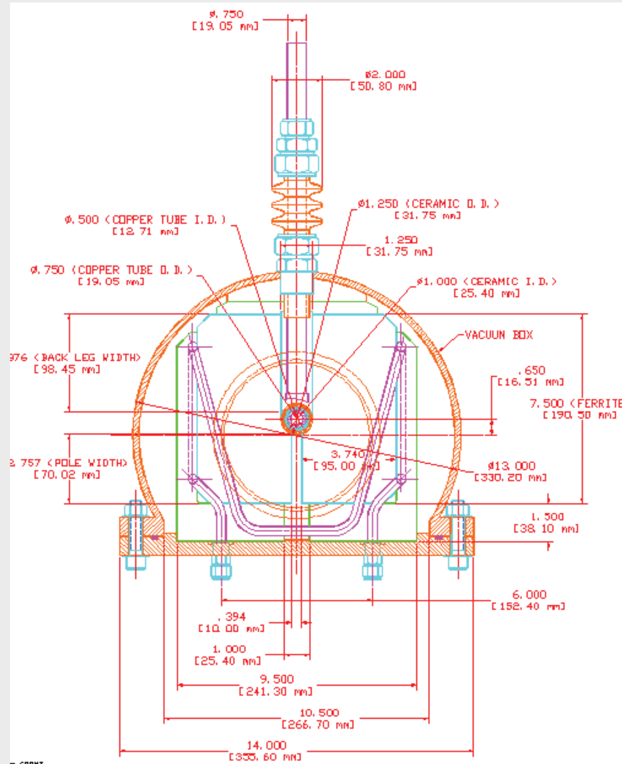


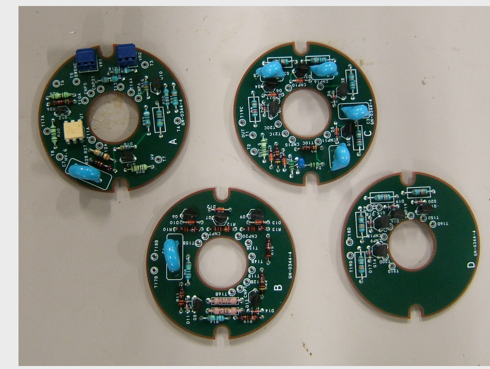
CDR under development

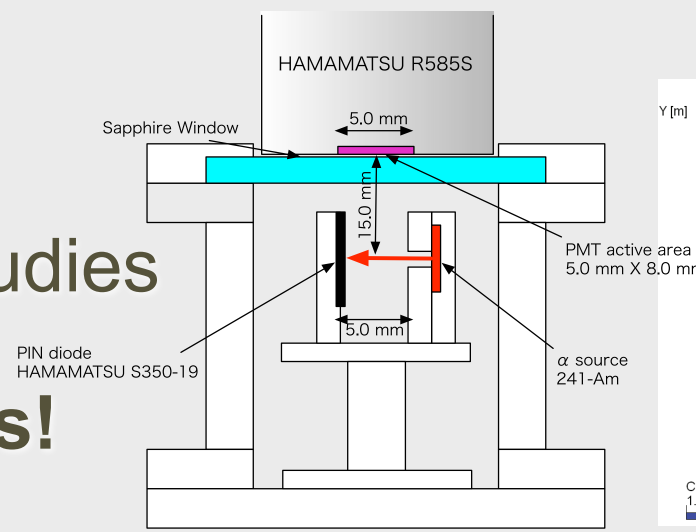
- "Switch" dipole timing to eliminate bunches, accept out-of-time protons for direct *measurement* of extinction

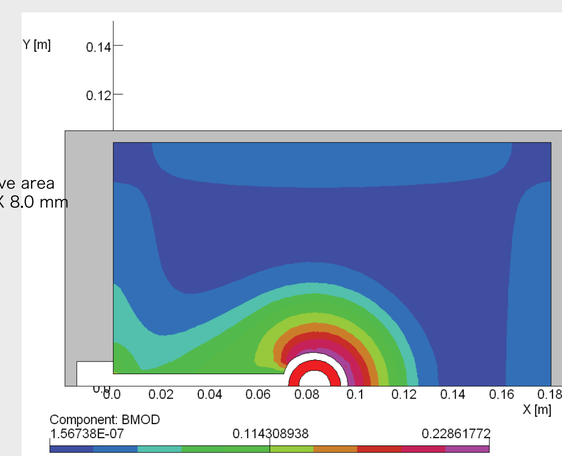
Collaboration with Japan

- COMET/Mu2e are collaborating on
  - AC Dipole (FNAL)
  - Extinction Monitor (Osaka)
- US-Japan Agreement
  - KEK/FNAL
- ~$50K this year for studies
- **Critical For Progress!**



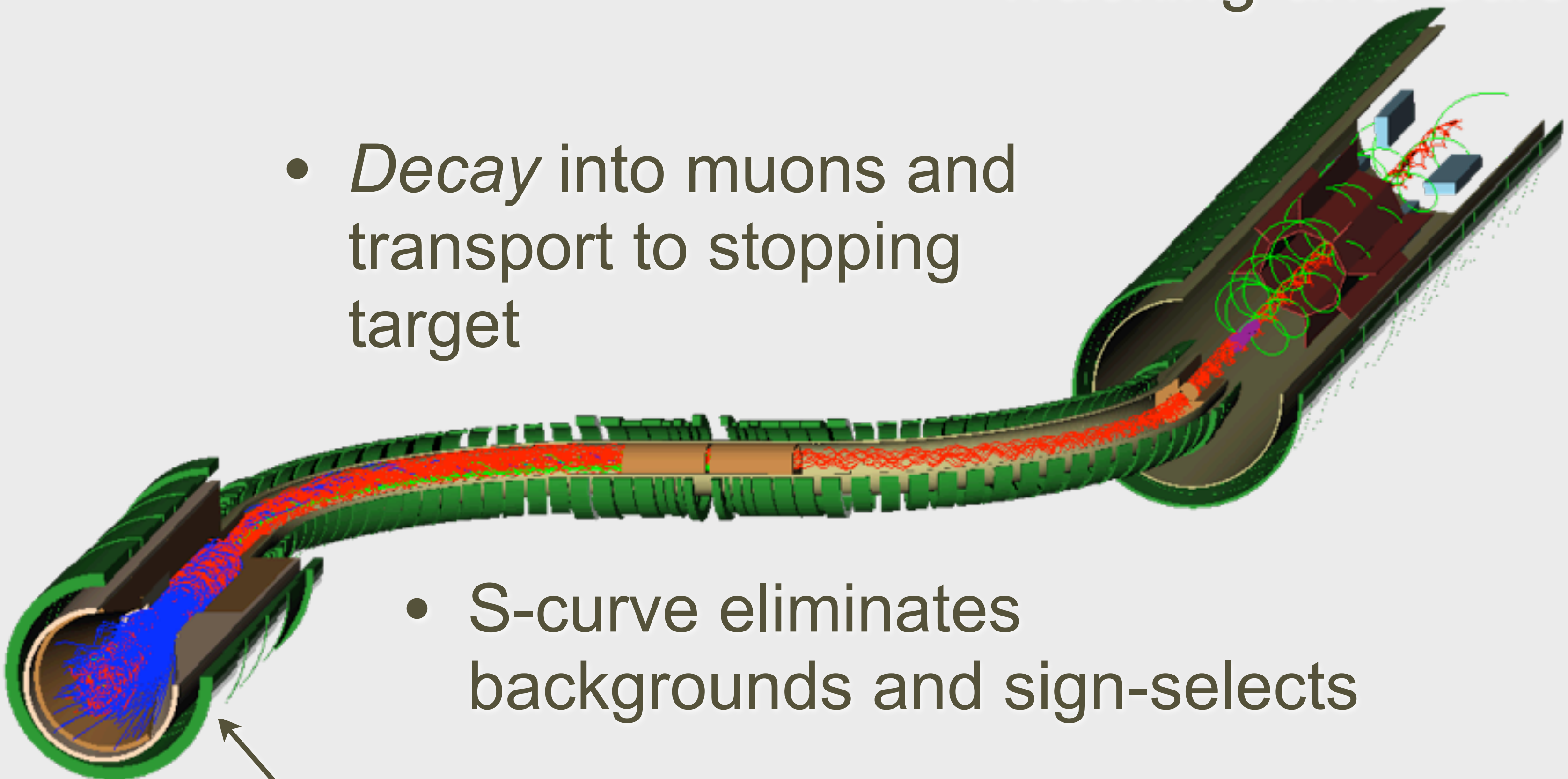






Detector and Solenoid

- *Tracking and Calorimeter*
- *Decay* into muons and transport to stopping target



- S-curve eliminates backgrounds and sign-selects
- *Production*: Magnetic bottle traps backward-going π that can decay into accepted μ's

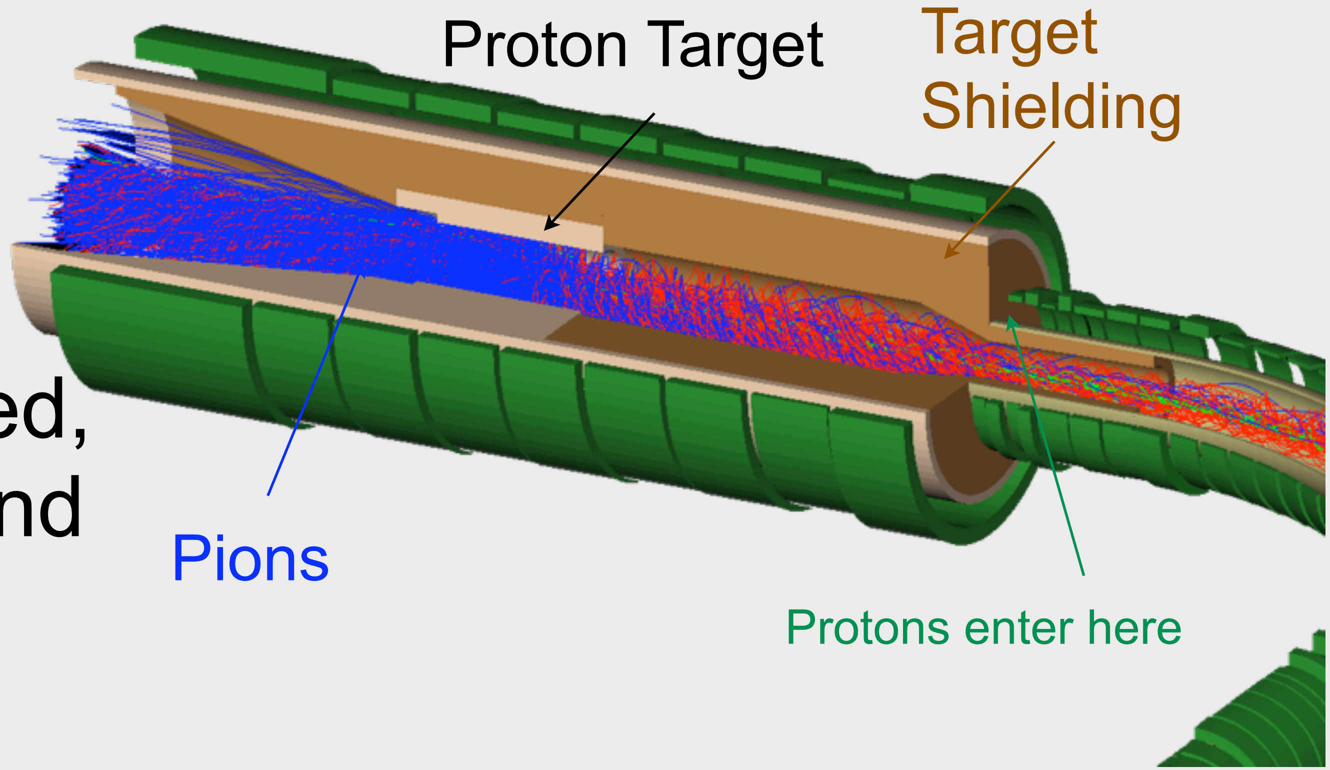
Production Solenoid:

Protons enter opposite to outgoing muons – this is a central idea to remove prompt background

Protons leave through thin window

π's are captured, spiral around and decay

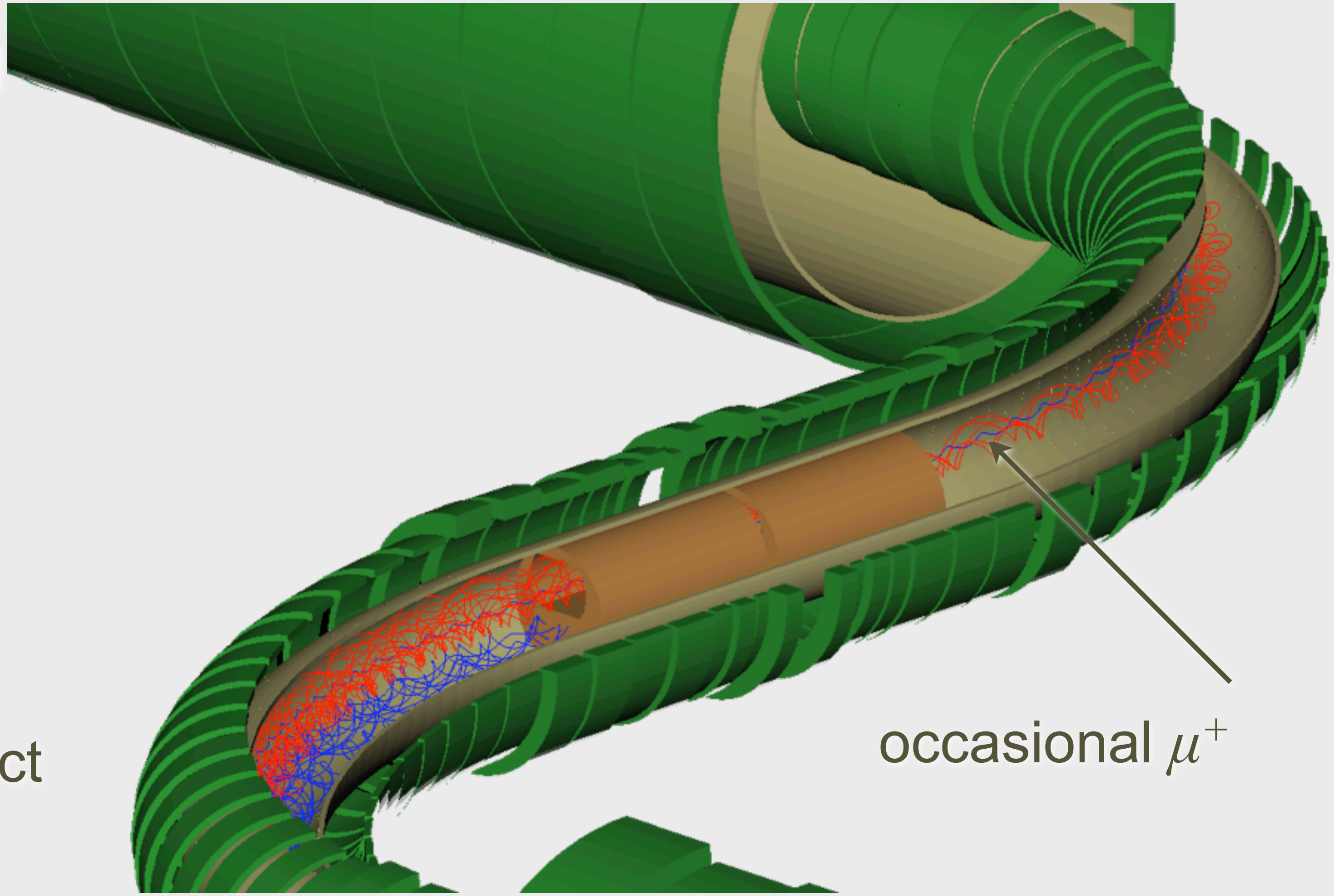
muons exit to right



4 m X 0.75 m

Transport Solenoid

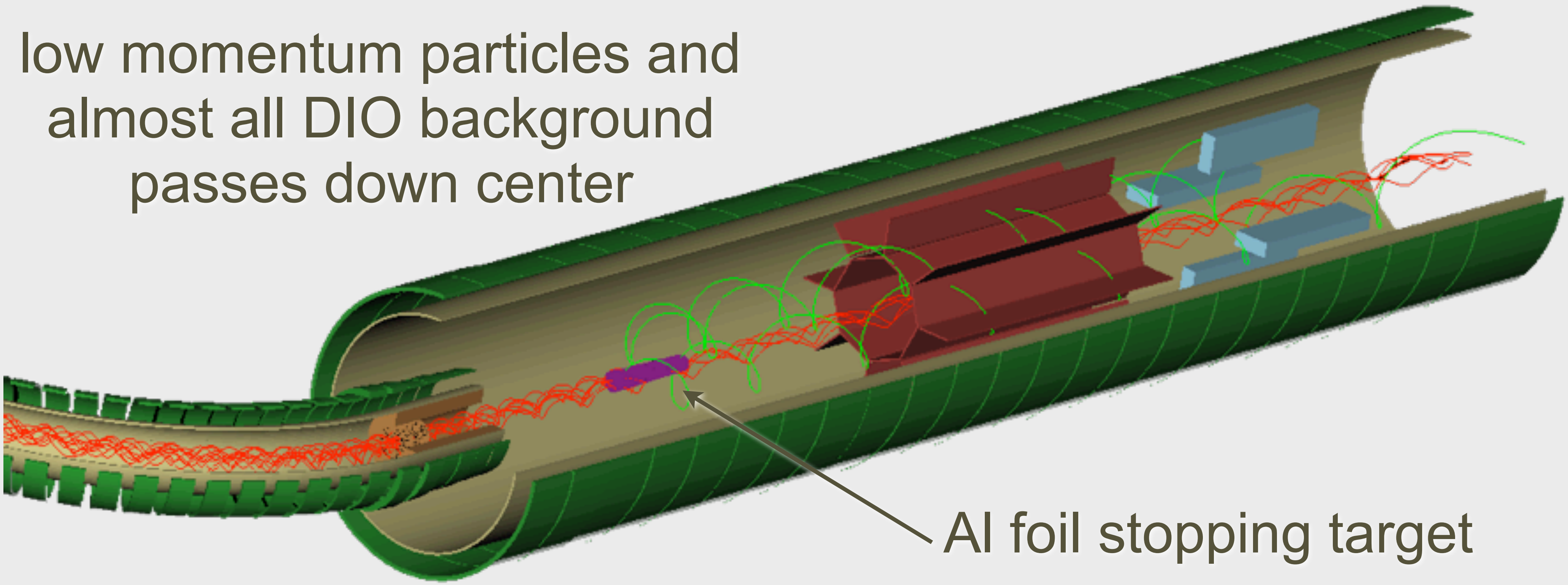
- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam



Detector Solenoid

octagonal tracker surrounding central region: radius of helix proportional to momentum

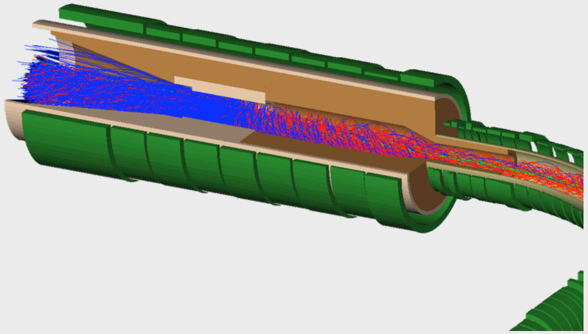
low momentum particles and almost all DIO background passes down center



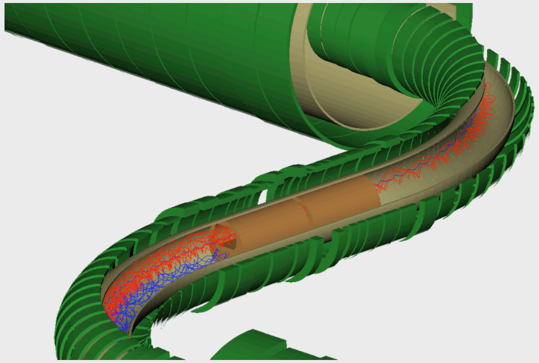
Al foil stopping target

signal events pass *through* octagon of tracker and produce hits

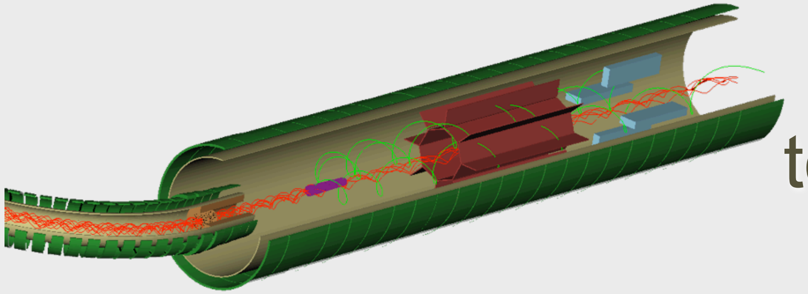
Graded Fields



Production Solenoid:
graded from ~5.0 to 2.5T
to (a) capture backwards-going pions
and allow them to decay and (b) “reflect”
backward-going muons



Transport Solenoid:
graded from ~2.5 to 2.0T
to accelerate muons along beamline



Detector Solenoid:
graded from ~2.0 to 1T
to “reflect” backwards-going electrons
and send them into detector

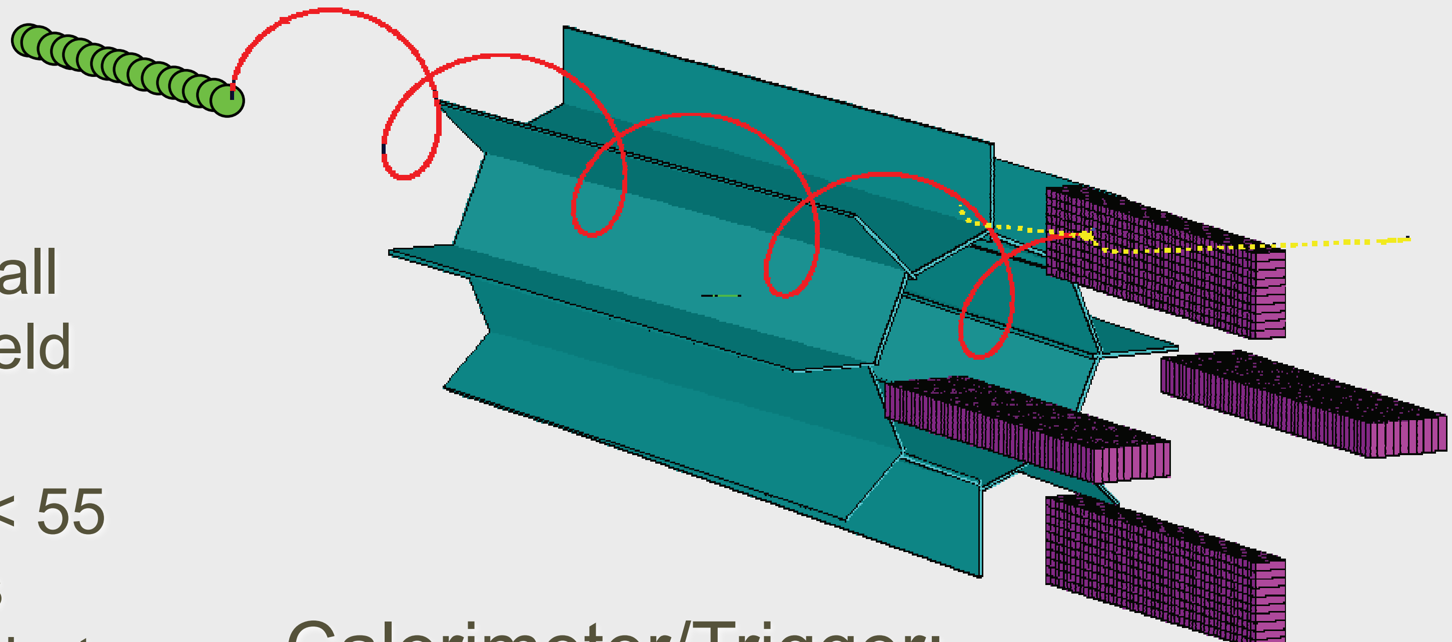
Detector

- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
  - up to dE/dx, scattering, small variations in field
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center

$\sigma = 200\ \mu$ transverse, 1.5 mm axially

2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick

use return yoke as CR shield

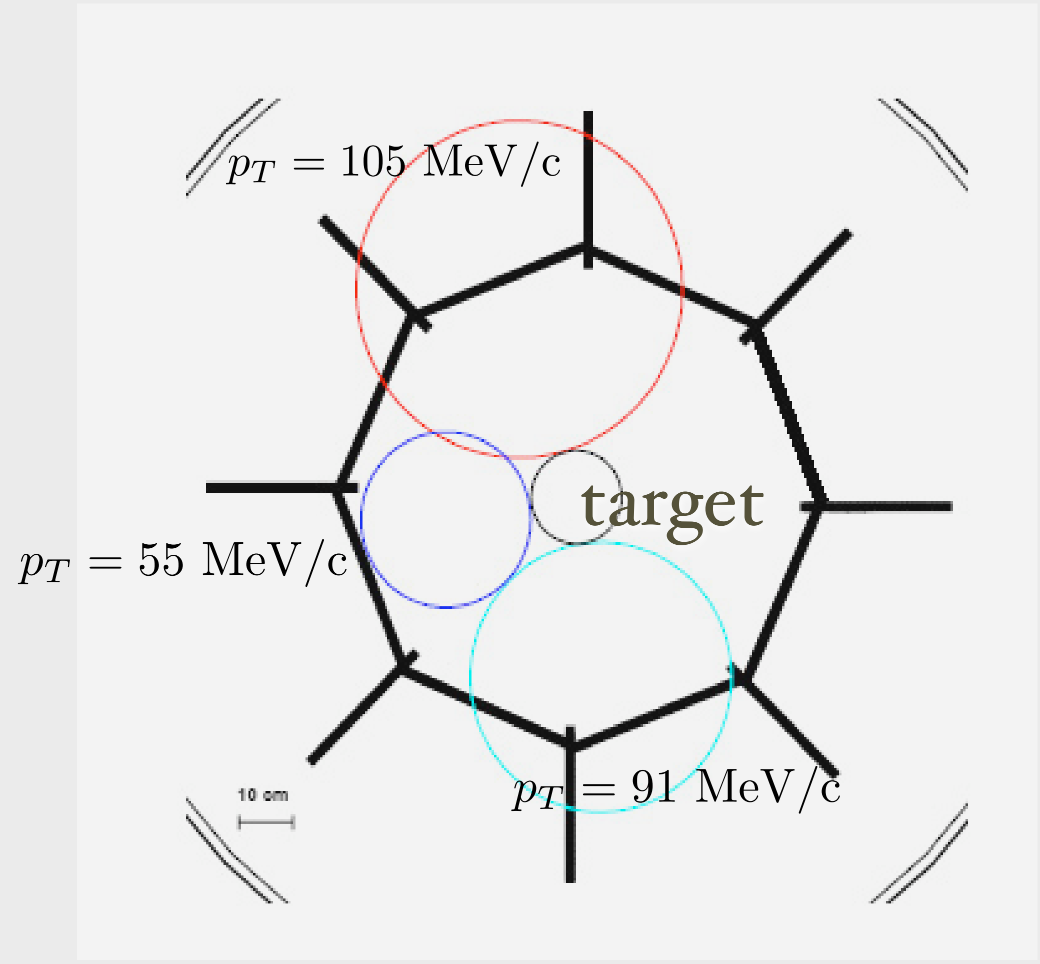


Calorimeter/Trigger:

$\sigma/E = 5\%$, 1200 $3.5 \times 3.5 \times 12$ cm $PbWO_4$

Beam's Eye View of Tracker

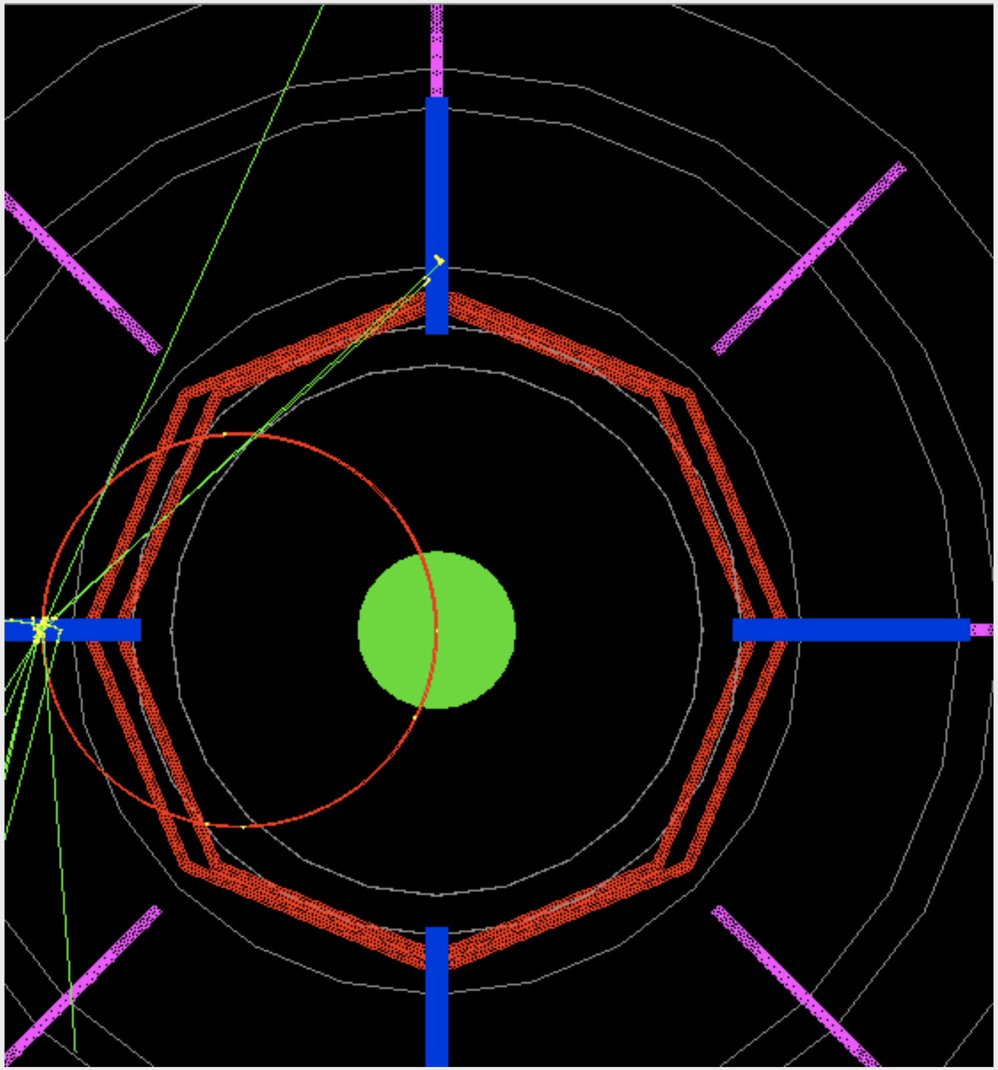
- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field
- Below p_T = 55 MeV, electron stays inside tracker and is not seen; about 60° at 103.5 MeV
- Looking for helix as particle propagates downstream



Note: < only 0.3% of e- from DIO have p_T>55 MeV/c

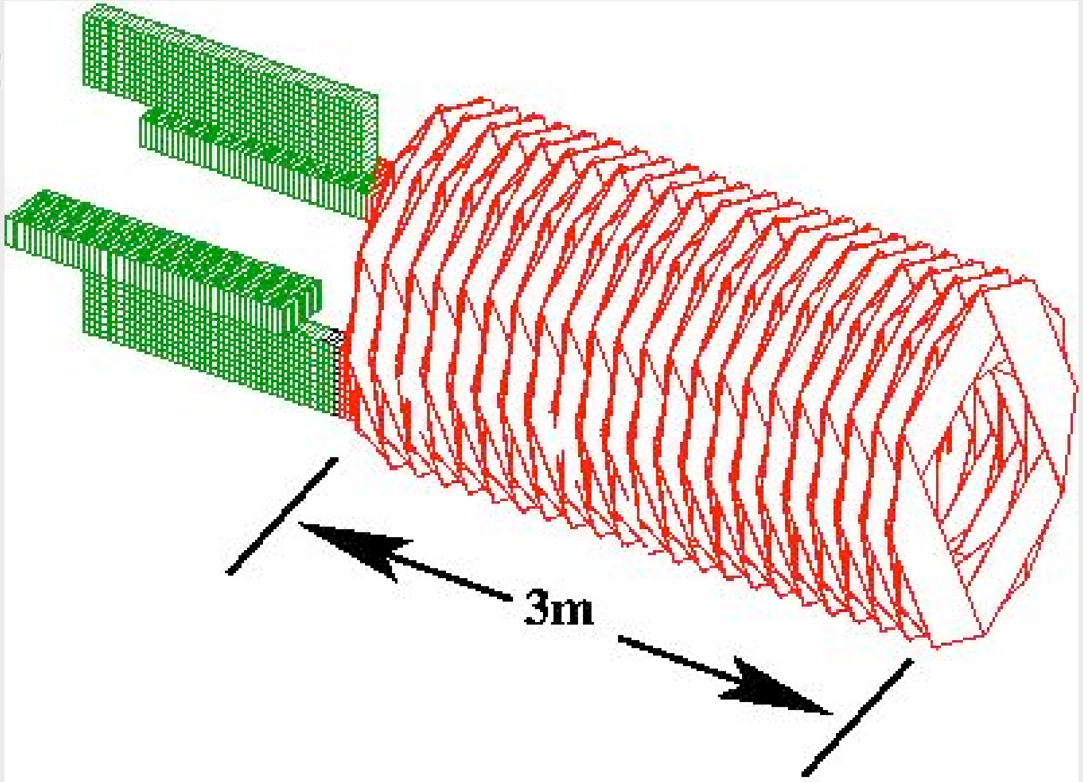
Details

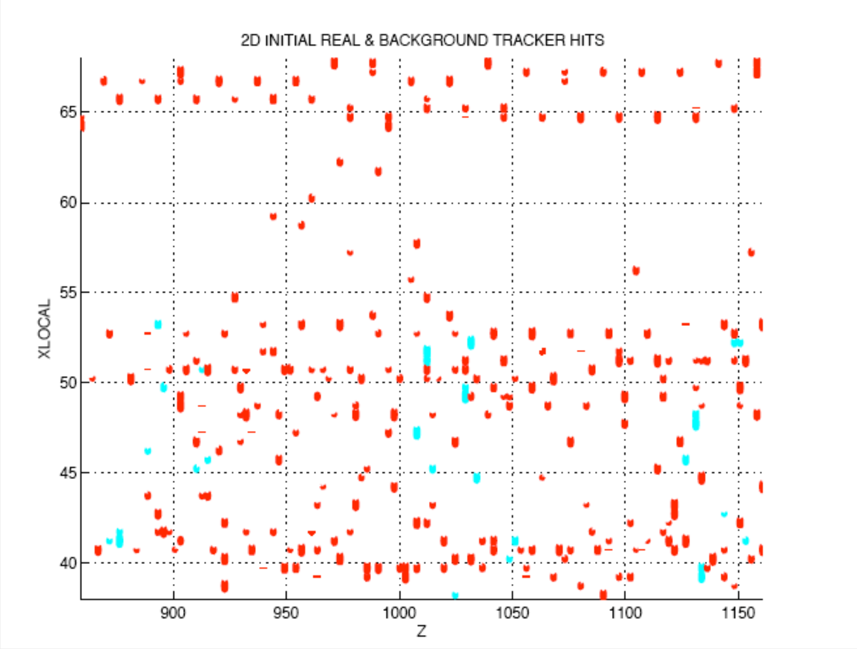
- 38 -70 cm active radius
- Geometry: Octagon with eight vanes, each ~30 cm wide x 2.6 m long
- Straws: 2.9 m length 5mm dia., 25 mm wall thickness to minimize multiple scattering – 2800 total
- Three layers per plane, outer two resistive, inner conducting
- Pads: 30 cm 5mm wide cathode strips affixed to outer straws - 16640 total pads
- Position Resolution: 0.2 mm (r,φ) X 1.5 mm (z) per hit
- Energy loss and straggling in the target and multiple scattering in the chambers dominate energy resolution of 1 MeV FWHM



Alternative Tracker

- T-tracker (T for transverse):
- 260 sub-planes
  - sixty 5 mm diameter conducting straws
  - length from 70-130 cm
  - total of 13,000 channels





T-Tracker Pattern Recognition Difficult but
Kalman Filter is promising

L-Tracker vs. T-Tracker

- L-Tracker: straws along beam
  - Conceptually simpler tracking
  - Basis of MECO
  - Where does support/ infrastructure go? Material in electron path
  - Can anyone build straws 0.5 cm × 2.6m in vacuum?
- T-Tracker: straws perp to beam
  - More prone to pattern recognition errors?
  - Active Investigation:
    - kalman filter, applied to both on same events
    - work just beginning
    - help welcome!

Backgrounds...

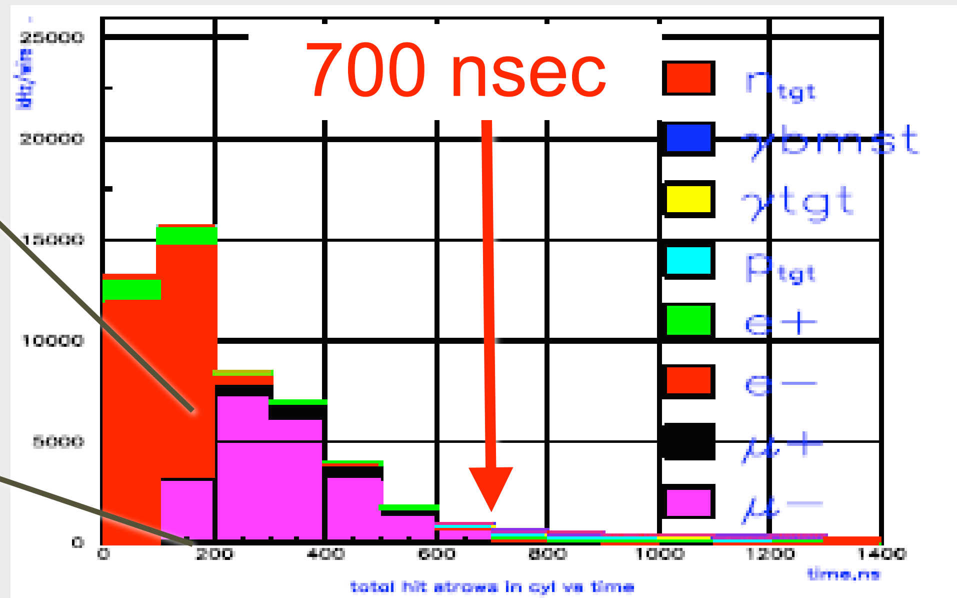
Type	Description
e_t	beam electrons
n_t	neutrons from muon capture in muon stopping target
γ_t	photons from muon capture in muon stopping target
p_t	protons from muon capture in muon stopping target
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, $<$ 55 MeV
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, $>$ 55 MeV
n_{bd}	neutrons from muon capture in beam stop
γ_{bd}	photons from muon capture in beam stop
$e(DIO)_{bd} < 55$	DIO from muon capture in beam stop, $<$ 55 MeV
$e(DIO)_{bd} > 55$	DIO from muon capture in beam stop, $>$ 55 MeV
$e(DIF)$	DIO between stopping target and beam stop

bd = albedo from beam stop (after calorimeter): splashback, extra hits confusing pattern recognition

Background Rates vs. Time

beam e-

μ DIF

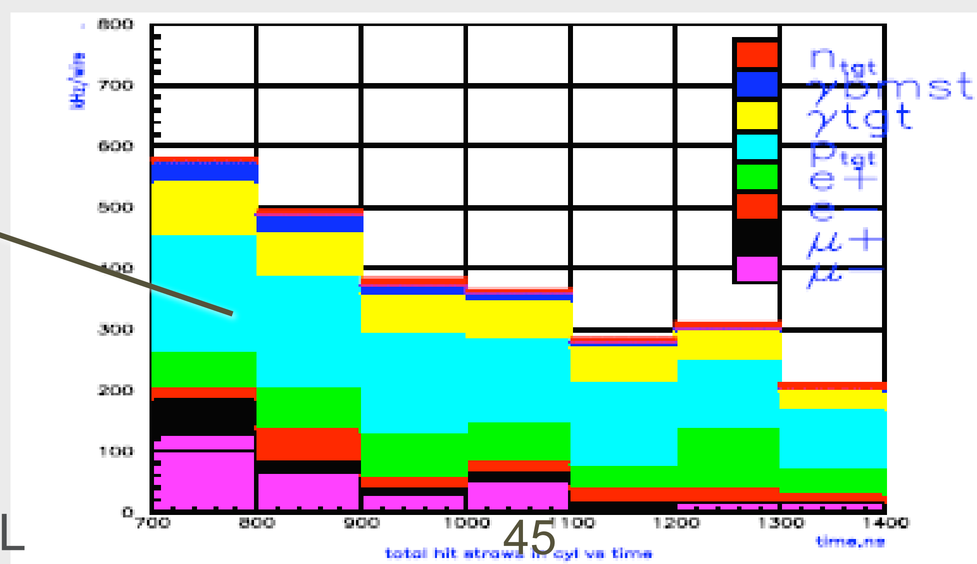


0-1400 nsec

Rate (15 MHz/wire)

divide by 4 FNAL/BNL

Protons in stopping tgt



700-1400 nsec

Rate (560 kHz/wire)

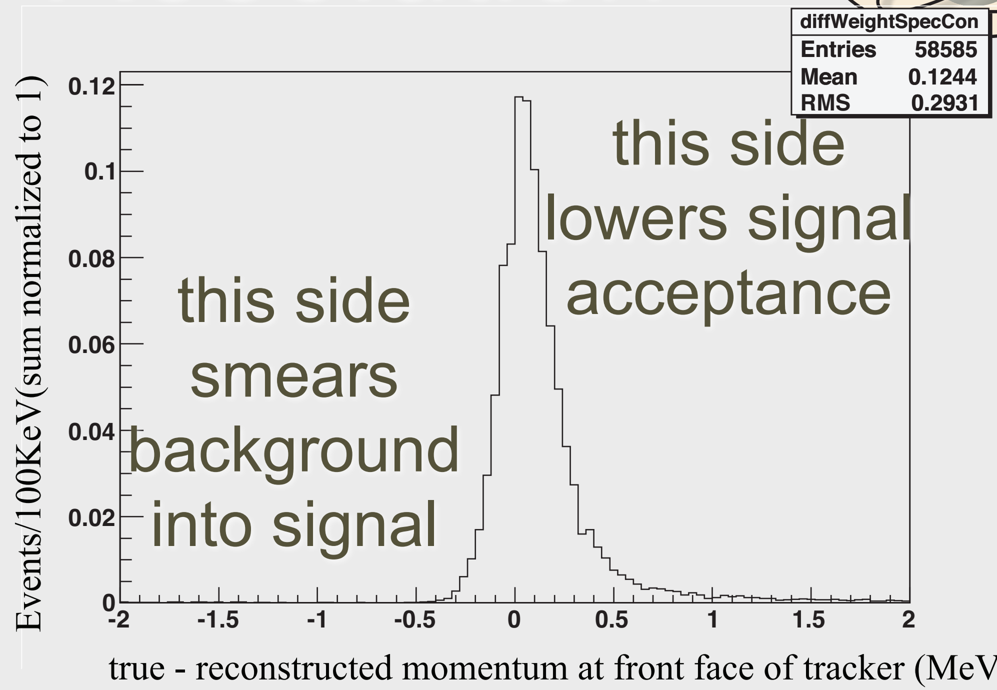
Rates In Tracker

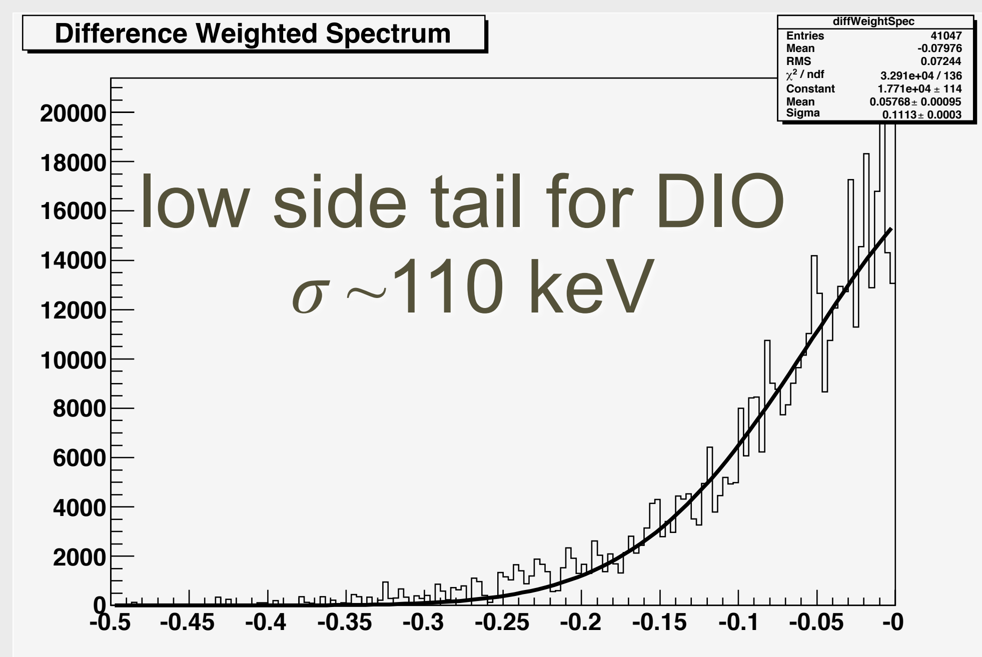
- Rates at Beginning of > 700 nsec Live Window, so these are highest
- ≈ 2 hits per straw during beam flash
- Rates are manageable: (1/4 of MECO instantaneous)

Type	Rate(Hz)	$\mathcal{P}$ hit	Mean N hits/bkg part	R_{wire} (kHz)
e_t	0.62×10^{11}	0.00032	1.54	16.3
n_t	0.62×10^{11}	0.000142	2.887	12
γ_t	0.62×10^{11}	0.000248	4.524	33.4
p_t	4.5×10^{9}	0.00362	6.263	50.
$e(DIO)_t < 55$	0.2×10^{11}	9.8×10^{-5}	1.44	1.4
$e(DIO)_t > 55$	0.5×10^{8}	0.00127	22.7	0.5
n_{bd}	0.12×10^{11}	7.1×10^{-5}	5.0	1.5
γ_{bd}	0.12×10^{11}	8.3×10^{-5}	4.5	1.5
$e(DIO)_{bd} < 55$	0.5×10^{11}	8.9×10^{-5}	1.	1.65
$e(DIO)_{bd} > 55$	1.4×10^{8}	1.82×10^{-4}	1.5	0.0125
$e(DIF)$	0.69×10^{6}	1	35.84	8.6
total				116

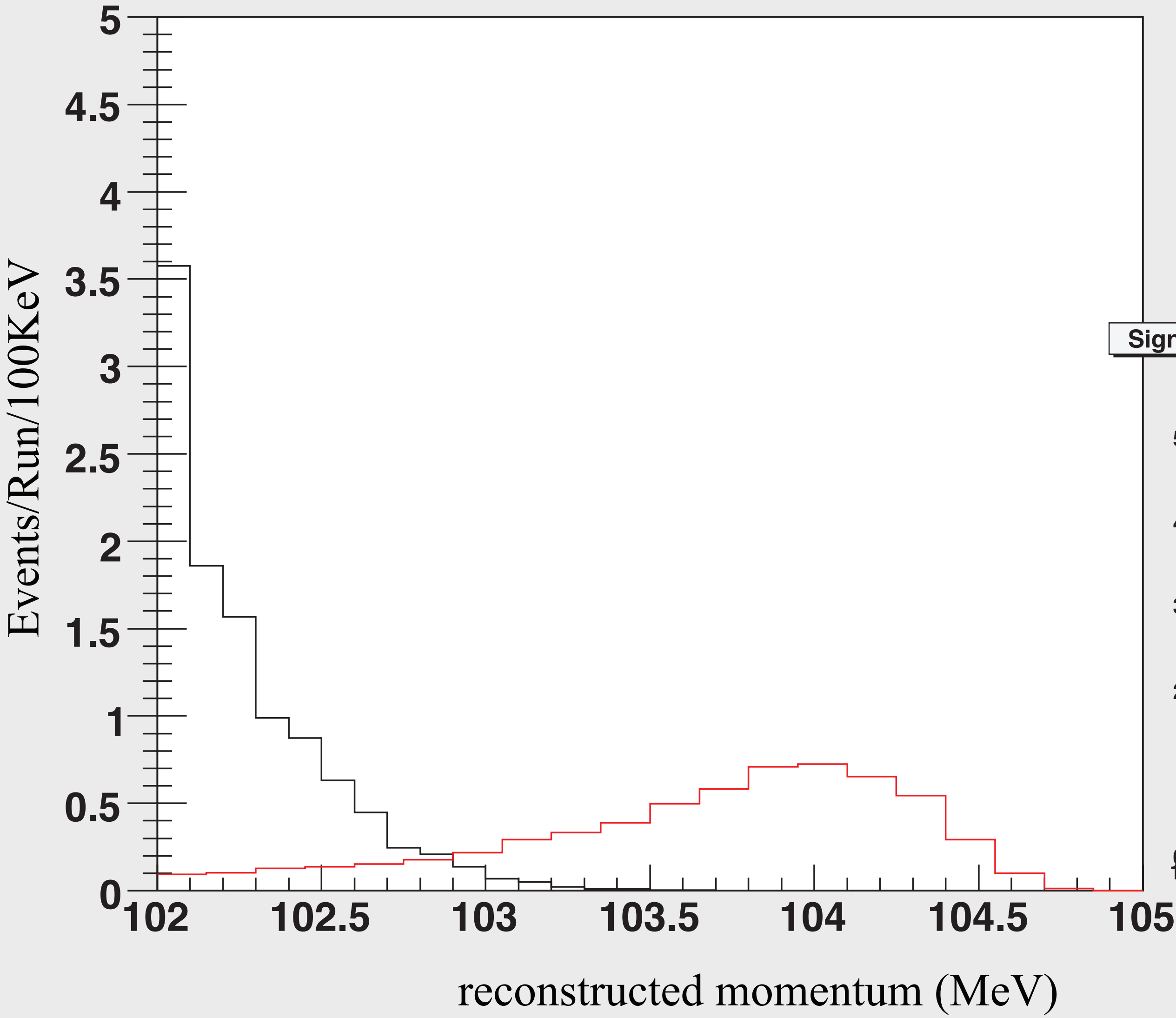
Expected Resolution

- We must understand resolution
- Measure resolution with special runs varying target foils, field, location of stopping target



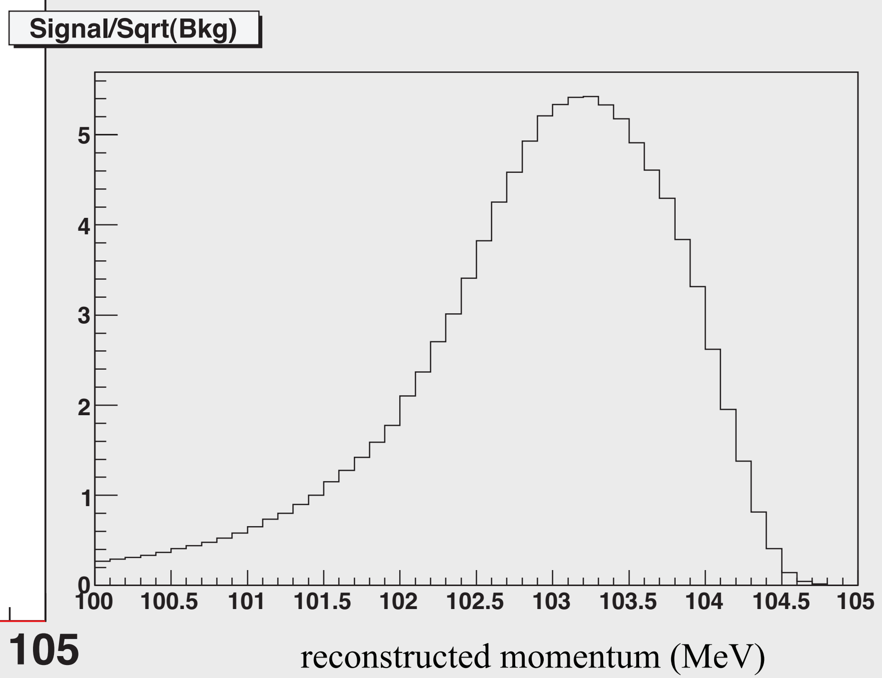


Signal and Background



- $R_{\mu e} = 10^{-16}$

$$\frac{S}{\sqrt{B}} \sim 5.5$$



Final Backgrounds

- For $R_{\mu e} = 10^{-16}$ expect ~5 events / 0.5 bkg
- Extinction factor of 10^{-9}

Source	Number/ 4 x 10^{20}
DIO	0.25
Radiative π capture	0.08
μ decay-in-flight	0.08
Scattered e-	0.04
π decay in flight	<0.004

Outline

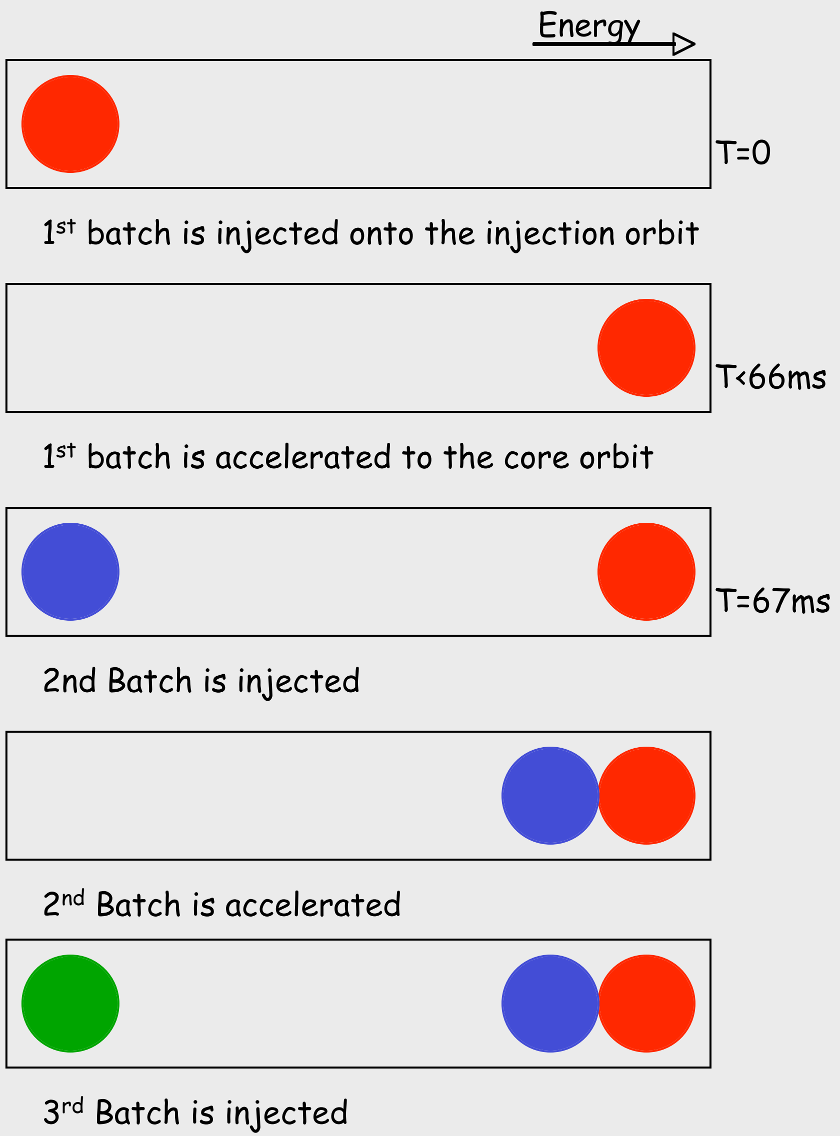
- The search for muon-electron conversion
- Experimental Technique
- *Fermilab Accelerator*
- Project X Upgrades and Mu2e

FNAL Beam Delivery

- Multiple Rings at FNAL
  - no interference with NOvA neutrino oscillation experiment
  - reuse existing rings with only minor modifications

Quick Fermilab Glossary

- Booster:
  - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
  - momentum stacking successive pulses of antiprotons now, 8 GeV protons later
- Debuncher:
  - smooths out bunch structure to stack more $\bar{p}$ now; rebunch for mu2e
- Recycler:
  - holds more $\bar{p}$ than Accumulator can manage, “store” here



NovA Era and Mu2e

- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz

booster batches

- Single-Turn Transfer to MI

NovA Era and Mu2e

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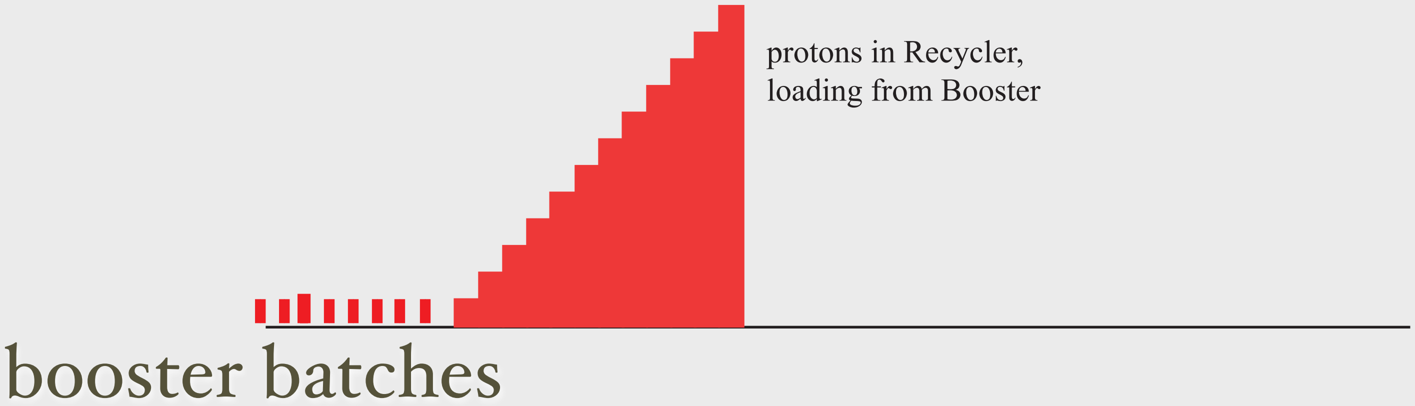

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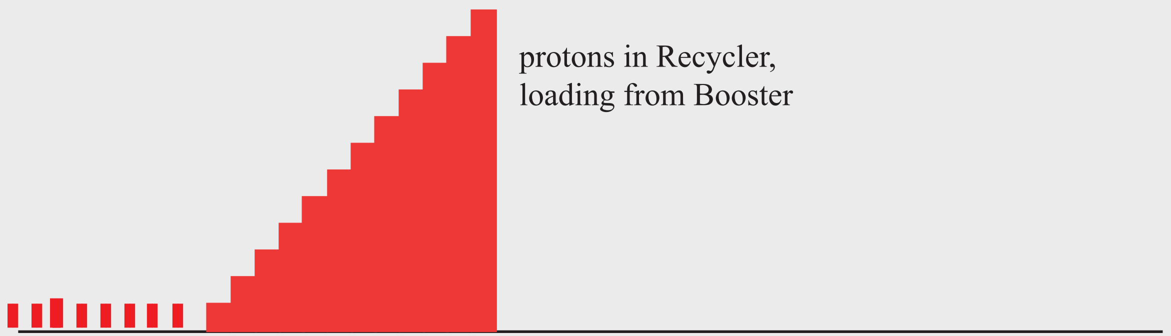

booster batches

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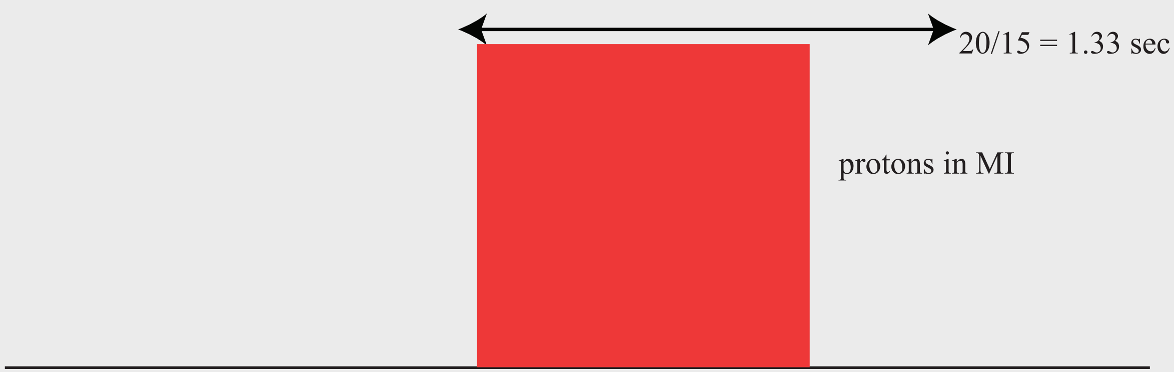

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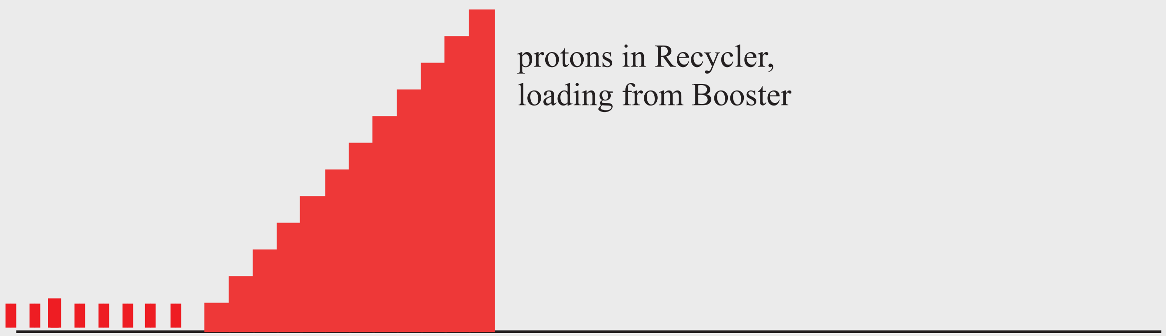

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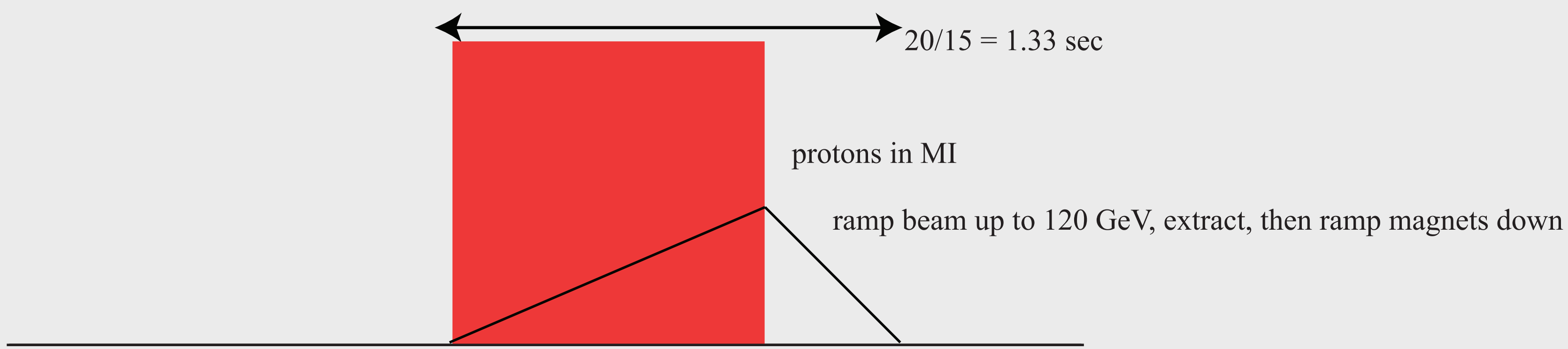
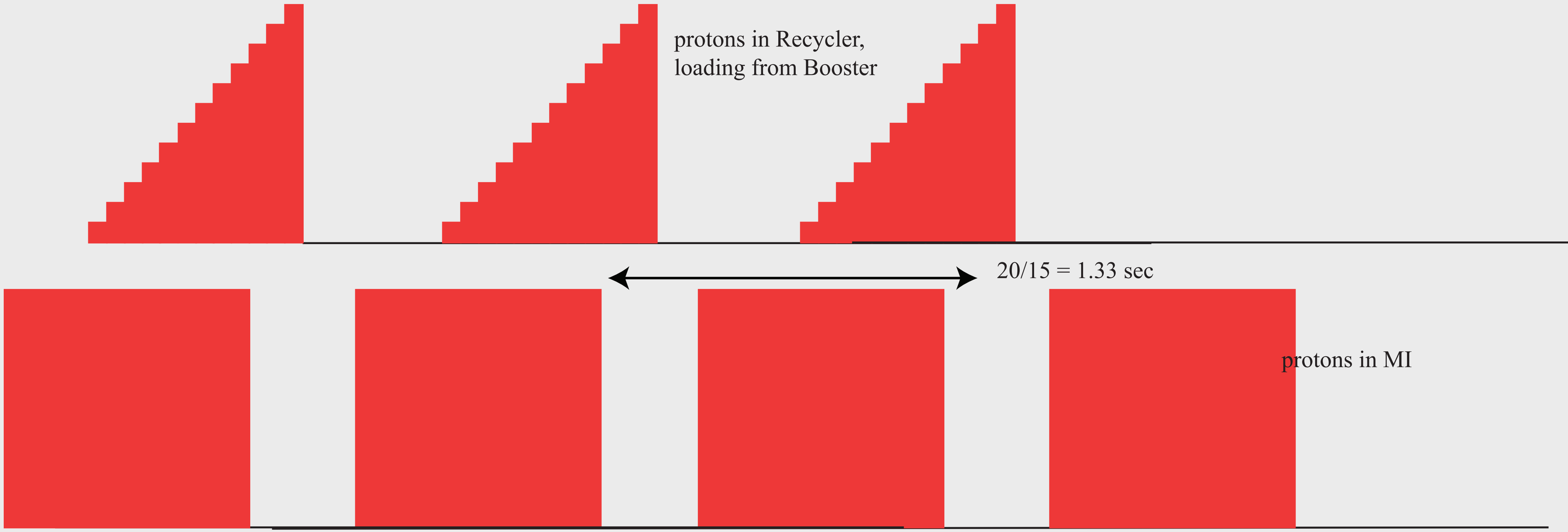
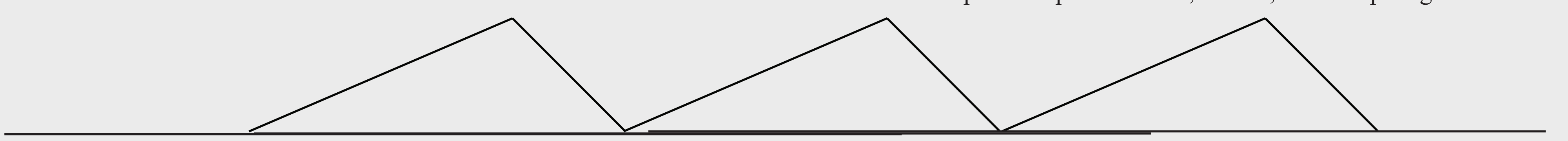


All Together...



time to ramp allows us to fit eight extra Booster batches for Mu2e (can use 6)



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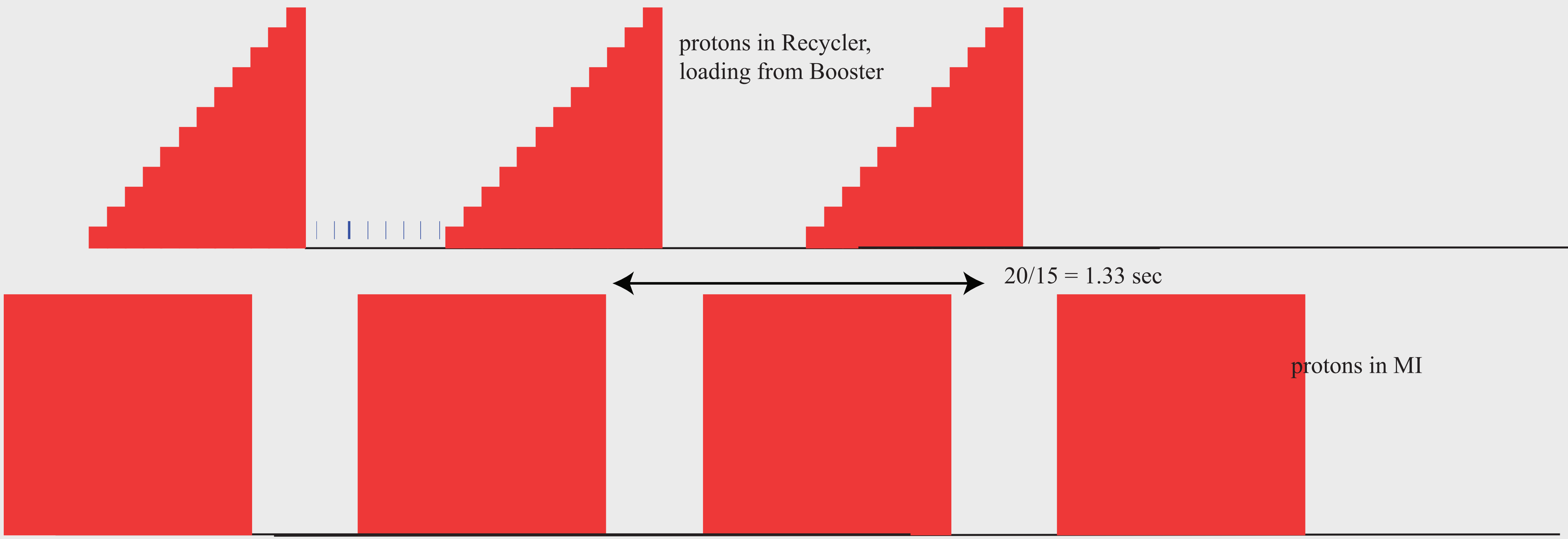

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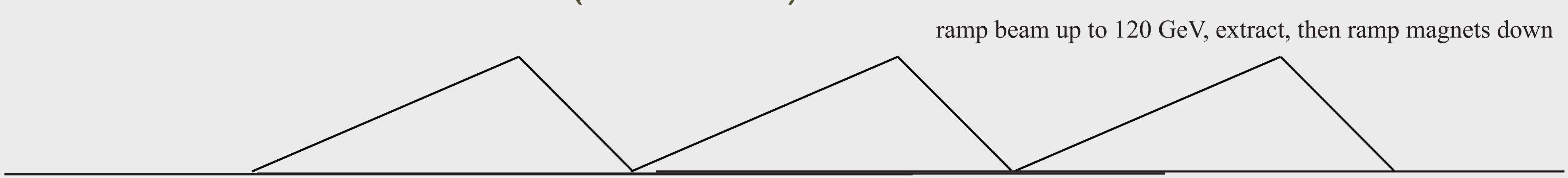
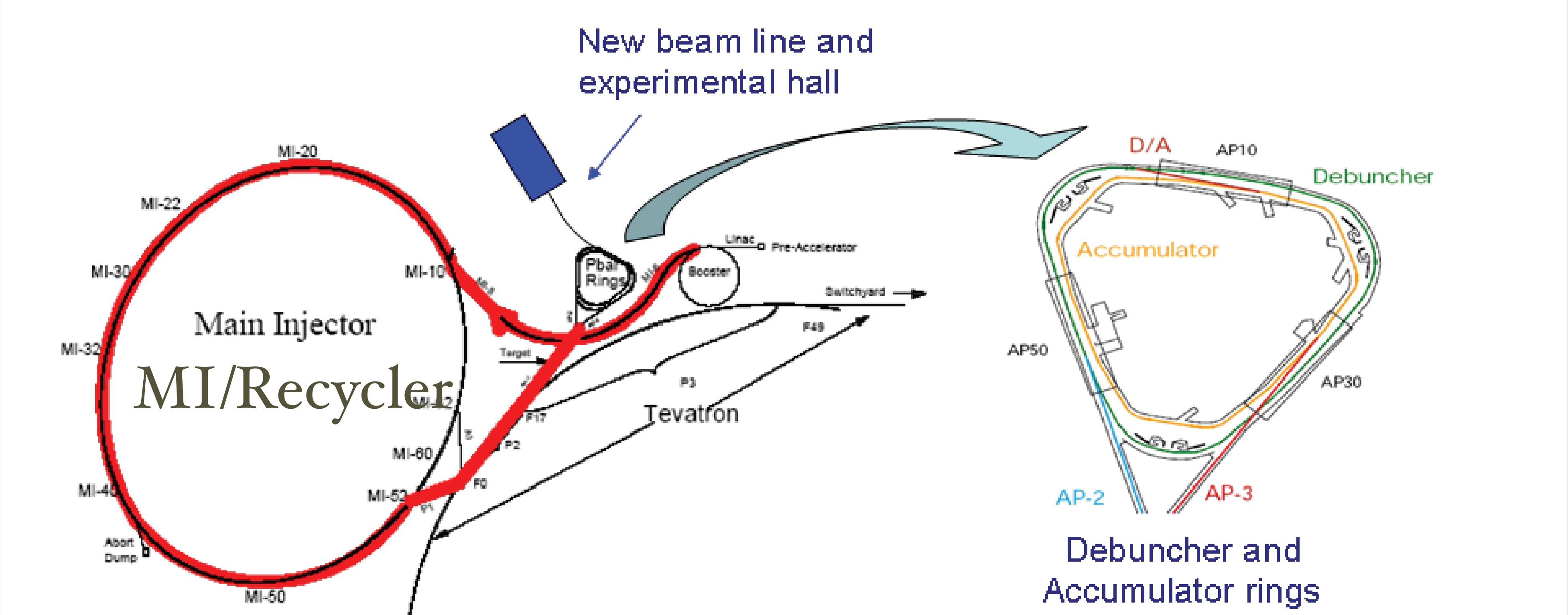


Booster-Era (before Project X) Beam

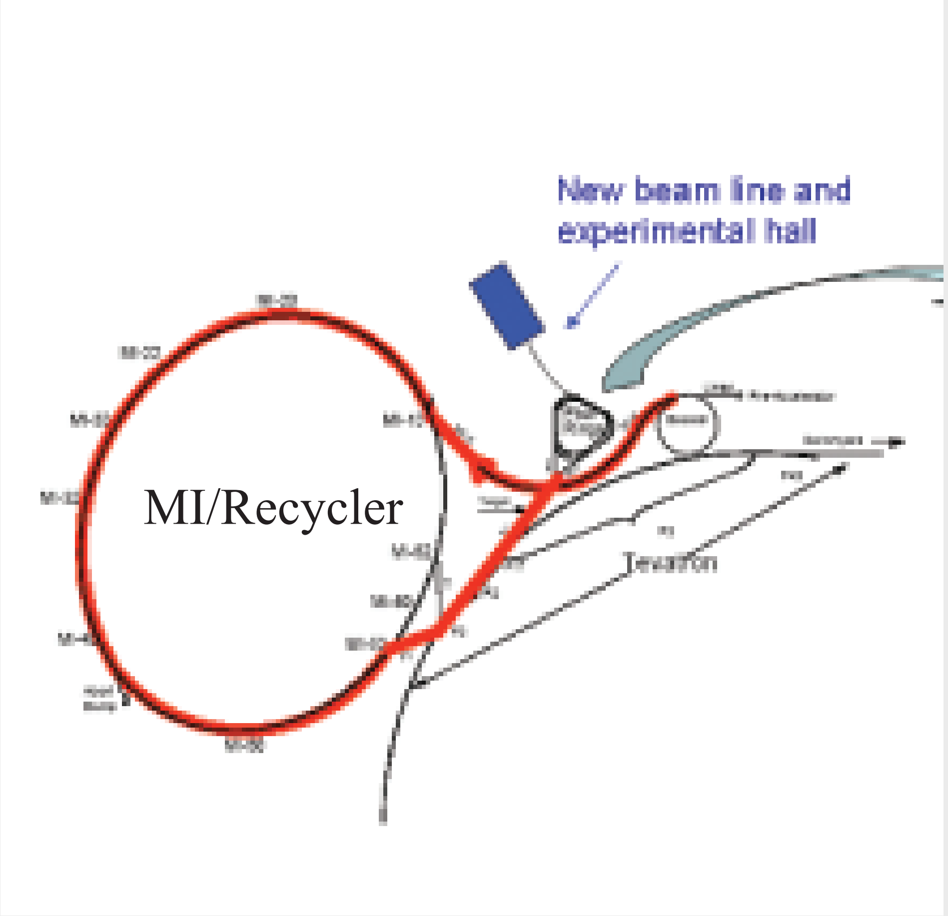


were used for $\bar{p}$

- After TeVatron shut-down, Accumulator, Debuncher, and Recycler no longer needed for antiprotons

“Boomerang Scheme”

- Booster Batches transported partway through Recycler and injected directly into Accumulator
- “Momentum-Stack” batches in Accumulator
- Transfer to Debuncher
- Rebunch into Single Bunch:
  - 38 nsec RMS, ±200 MeV
- Slow Extraction: transverse, yields bunch “train”
- Resonant Extraction of Bunch



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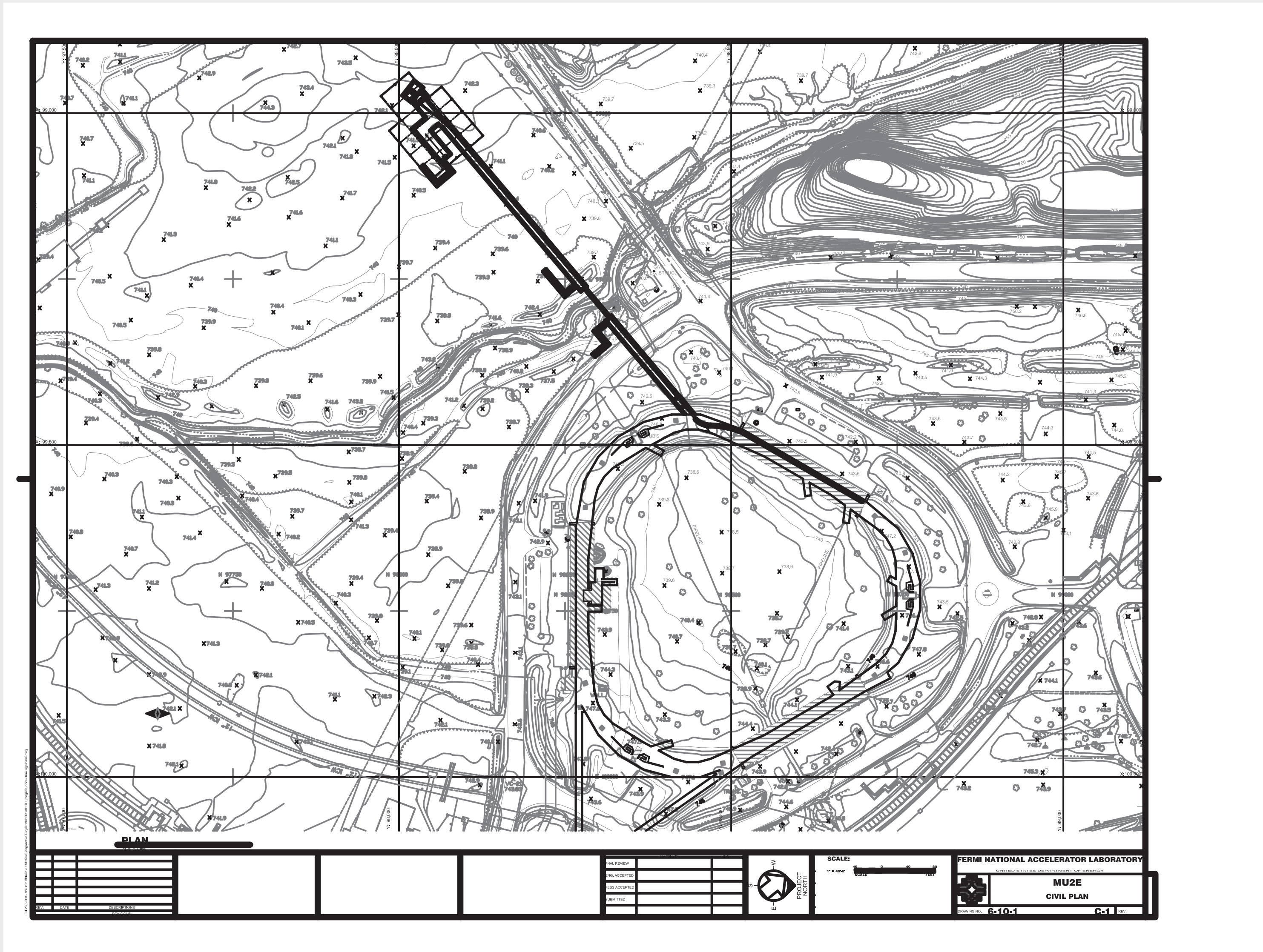
Proposed Site



Cost and Schedule

- A detailed cost estimate of the MECO experiment performed just before RSVP was cancelled: (in Actual Year $, including inflation)
  - Solenoids and cryogenics: $59M
  - Remainder of experimental apparatus: $21M
  - Additional Fermilab costs have not been worked out in detail
    - accelerator and civil construction costs are being worked out
  - Estimate for contingency, overhead, etc then yields $120M before beamline and civil costs

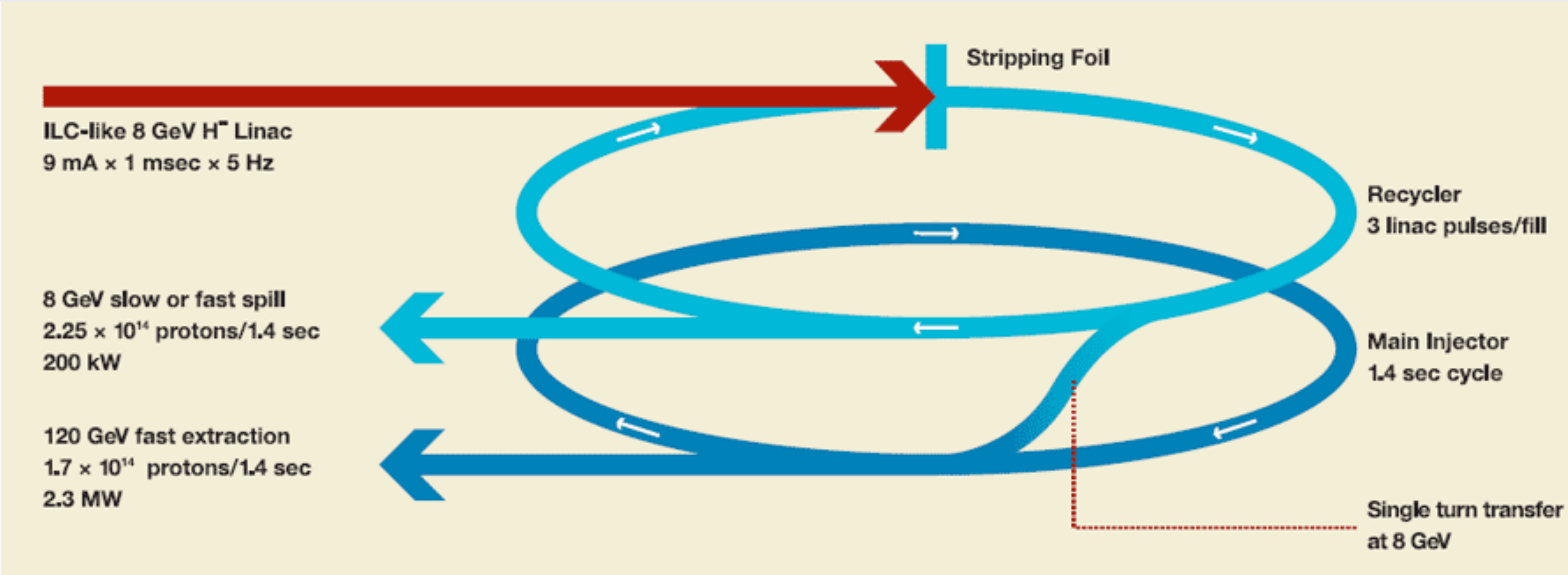
Schedule: 2016 for commissioning

- Based on the original MECO proposal, we believe the experiment could be operational within 3-4 years of “CD-2/3a”
  - Use NOνA experience for time for DOE Approval Process
  - Use MECO schedule for Technical Issues, especially solenoid construction
- *Aggressive but possible*

Outline

- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e

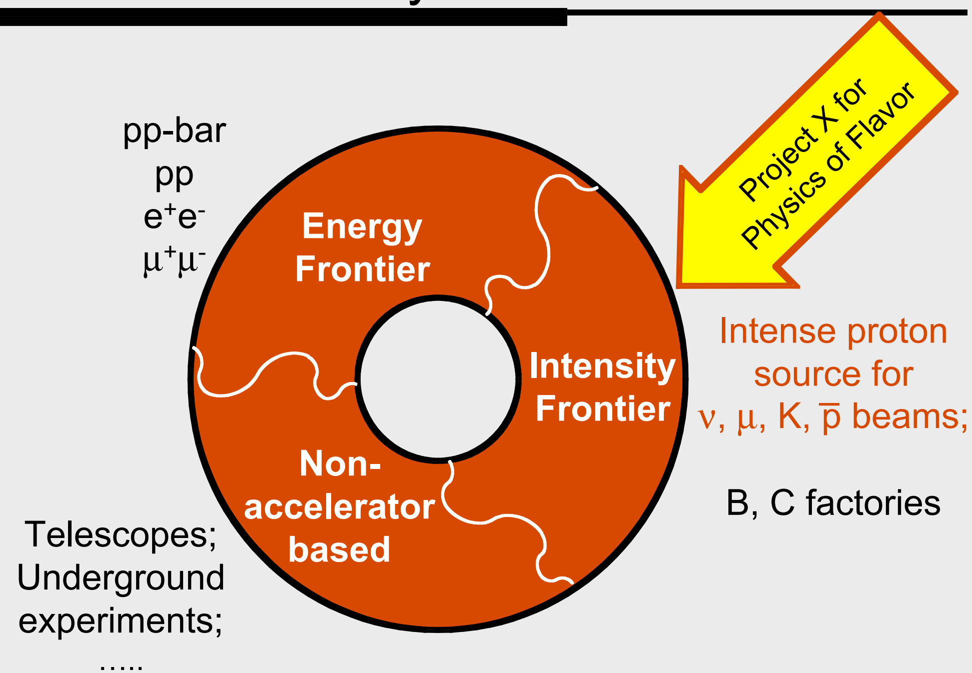
What is Project X?



- Project X is a concept for an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.
- The source consists of an 8 GeV superconducting linac that injects into the Fermilab Recycler

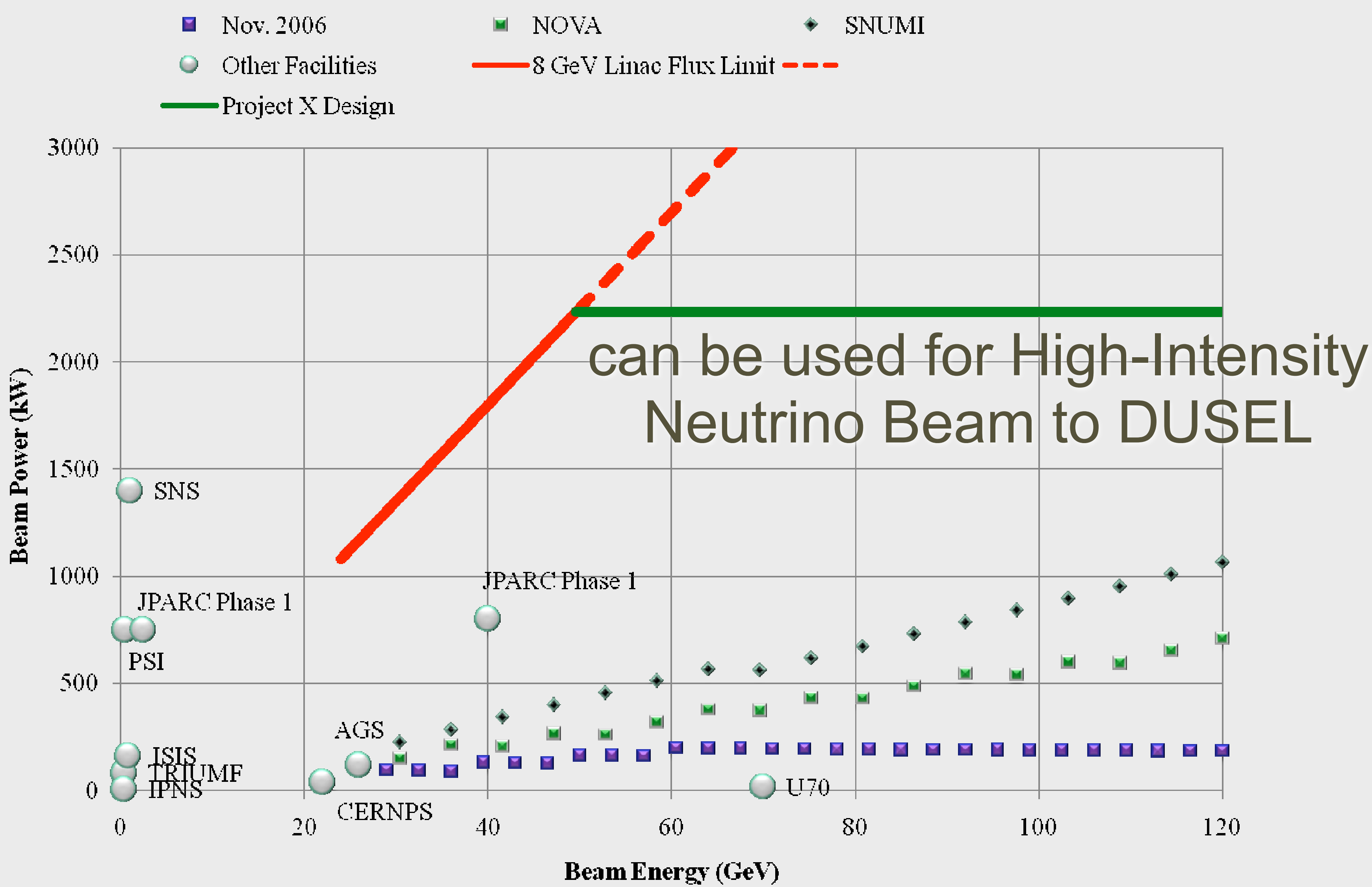
Why Project X?

Tools for Particle Physics



- FNAL Booster cannot provide sufficient intensity for the Intensity Frontier Program: neutrinos, muons, kaons,...

Project X Intensity Goals



Mu2e and Project X

- Project X is **required** for the next step
- Needed whether first phase sees a signal or sets a limit
- Well timed for Mu2e first phase, late this decade or early next

available 8 GeV Power for intensity frontier

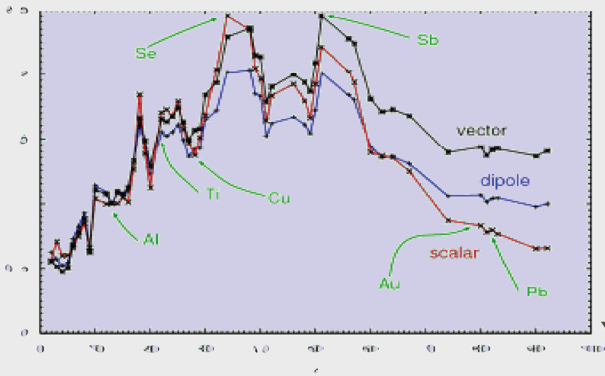
20 kW
(*current*)

200 kW
(**Project X**)

2000 kW

(***Project X Upgrades***)

Mu2e Phase II



Signal?

Yes

1. Change Z of Target to determine source of new physics

2. Need Project X to provide statistics

No

1. Probe additional two orders of magnitude made possible by Project X

2. Need upgrades to muon transport and detector

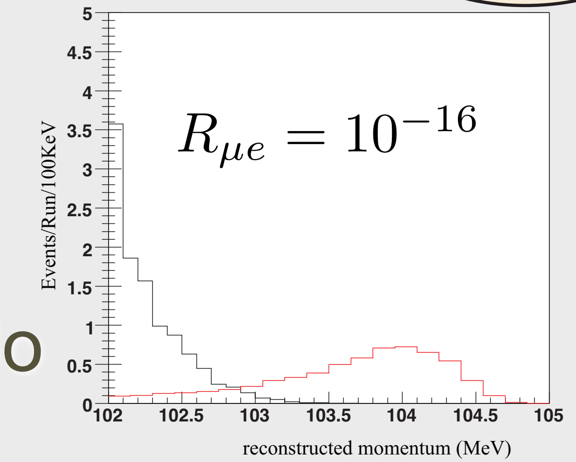
Experimental Challenges

Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au (79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible

Signal?

Yes

No



1. Change Z of Target to determine source of new physics

2. Prompt Rates will go up at higher Z, have to redesign detector and muon transport

1. Both Prompt and DIO backgrounds must drop x100 to measure $R_{\mu e} = 10^{-17}$

2. Detector, Muon Transport, Cosmic Ray Veto, Calorimeter

Project X Timing

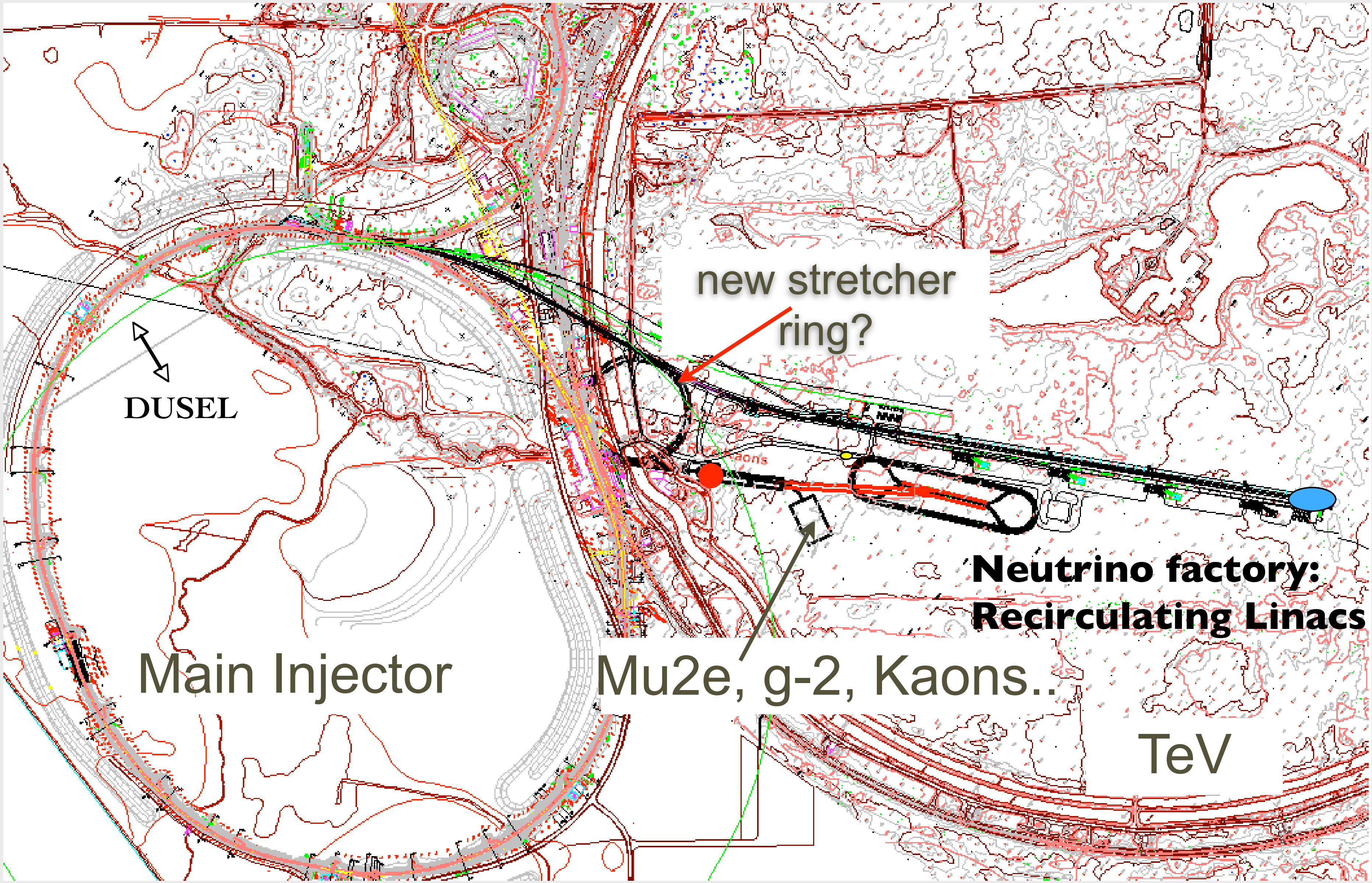
- Must run and analyze Mu2e Phase I
- We will continue to refine our existing design and look for new ideas
  - solenoid? tracking? time structure?
- Finish analysis Phase I around 2020

then

- ***Project X*** *makes a* ***program*** *possible, improving as we learn*

Project X Era?

not approved or part of any official plan...



Conclusions

- In the initial phase (without Project X) we would either:
  - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude (${R_{\mu e}} < 6 \times 10^{-17}$ @ 90% C.L.)*
  - *Discover unambiguous proof of Beyond Standard Model physics*
- With a combination of Project X and/or improved muon transport, we could either
  - *Extend the limit by up to two orders of magnitude*
  - *Study the details of new physics*

BACKUPS

Summary

Sensitivity Better than MECO

	MECO	Mu2e Booster	Mu2e Project X, no expt. upgrade	Mu2e Project X, expt. upgrade
protons/sec	40×10^{12} (design)	18×10^{12}	70×10^{12}	160×10^{12}
average beam power	50 kW (design)	23 kW	90 kW	200 kW
duty factor	0.5 s on, 0.5 s off, 50%	75-90%	75-90%	75-90%
instantaneous rate	**80×10^{12} (design)**	**20×10^{12}**	**77×10^{12}**	220×10^{12}
short term beam power	100 kW (design)	**25 kW**	100 kW	220 kW
Beam pulse period, msec	1.35	1.65	1.65	1.65
Data collection time interval msec	0.7-1.35	0.7-1.65	0.7-1.65	0.7-1.65

Summary

Sensitivity Better than MECO

if MECO could handle rates, Mu2e at FNAL can as well: pre-project X or with Project X

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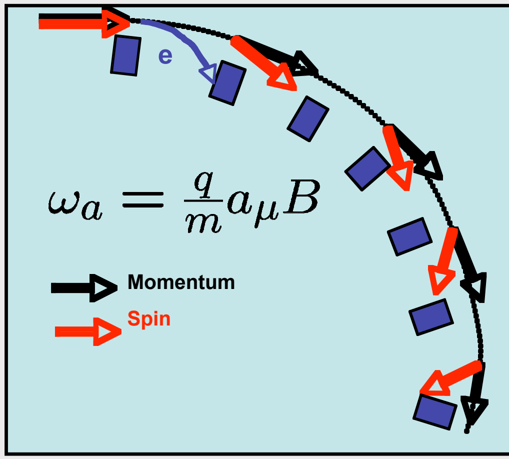
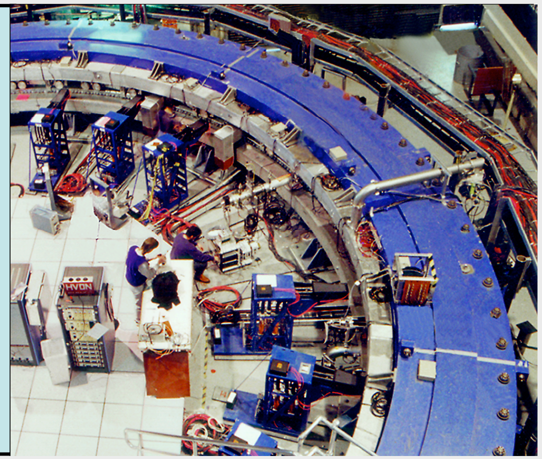
short term beam power	100 kW (design)	**25 kW**	100 kW	220 kW
Beam pulse period, msec	1.35	1.65	1.65	1.65
Data collection time interval msec	0.7-1.35	0.7-1.65	0.7-1.65	0.7-1.65

g-2 At Fermilab

$$\Delta a_\mu = a_\mu^{(\mathrm{Exp})} - a_\mu^{(\mathrm{SM})} \quad = 295 \pm 88 \times 10^{-10}$$

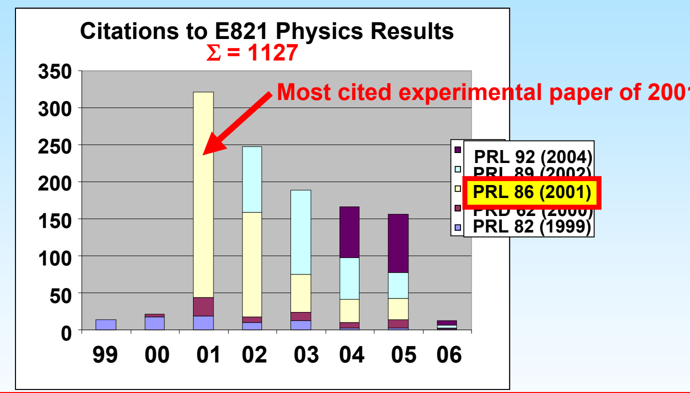




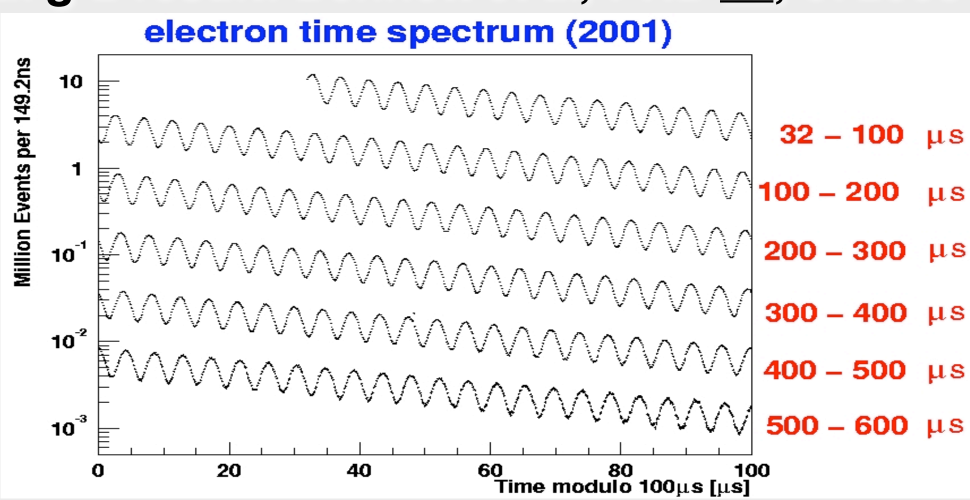
from 3.6σ → >7σ

current
$$\sigma_{\mathrm{stat}} = \pm 0.46 \text{ ppm}$$
$$\sigma_{\mathrm{syst}} = \pm 0.28 \text{ ppm}$$

This large number of citations demonstrate widespread interest in the community.



final g-2 result: Bennett et al, PRD 73, 072003 (2006)



Precision measurements provide an alternate path to the frontier of particle physics. Whatever LHC finds, muon (g-2) will provide independent constraints on the parameter space for new physics.

$$\Delta a_\mu^{\mathrm{MSSM}} \approx 130 \times 10^{-11} \tan\beta \, \mathrm{sign}(\mu) \left(\frac{100\,\mathrm{GeV}}{M_{\mathrm{SUSY}}} \right)^2$$

g-2 Method

We measure the difference frequency between the spin and momentum precession

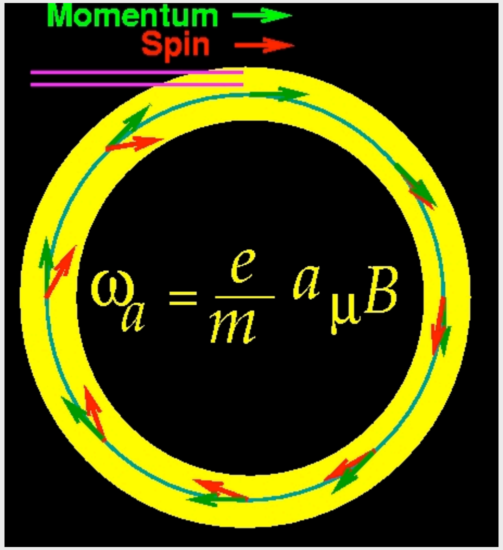
$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} \qquad B \Rightarrow \langle B \rangle_{\mu-\mathrm{dist}}$$

With an electric quadrupole field for vertical focusing

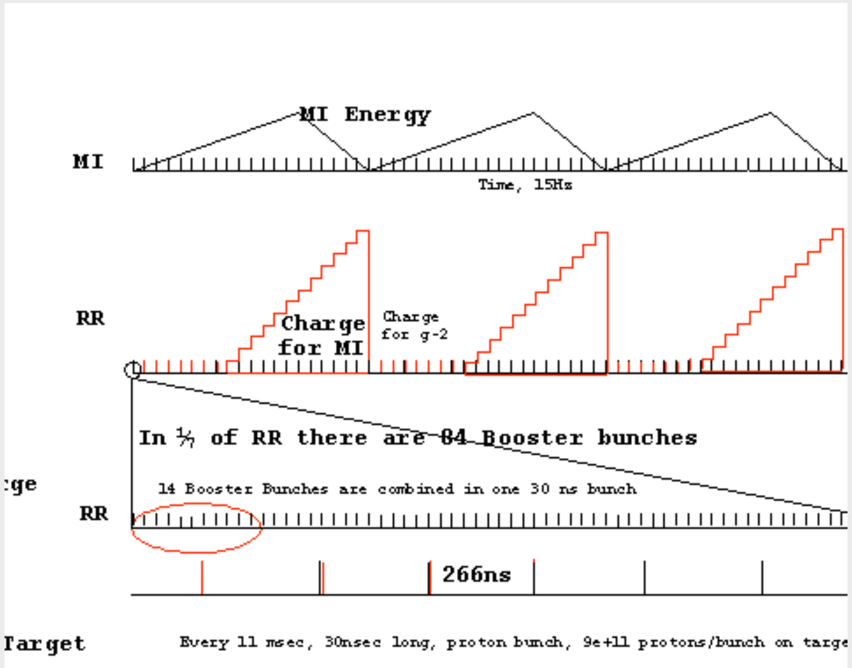
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \cancelto{0}{\frac{1}{\gamma^2-1}}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$\gamma_{\mathrm{magic}} = 29.3$$

$$p_{\mathrm{magic}} = 3.09\ \mathrm{GeV/c}$$



Possible Beam Scheme



- use Accumulator/Debuncher to produce correct time structure
- house in new building near AP0
- runs *before* Mu2e

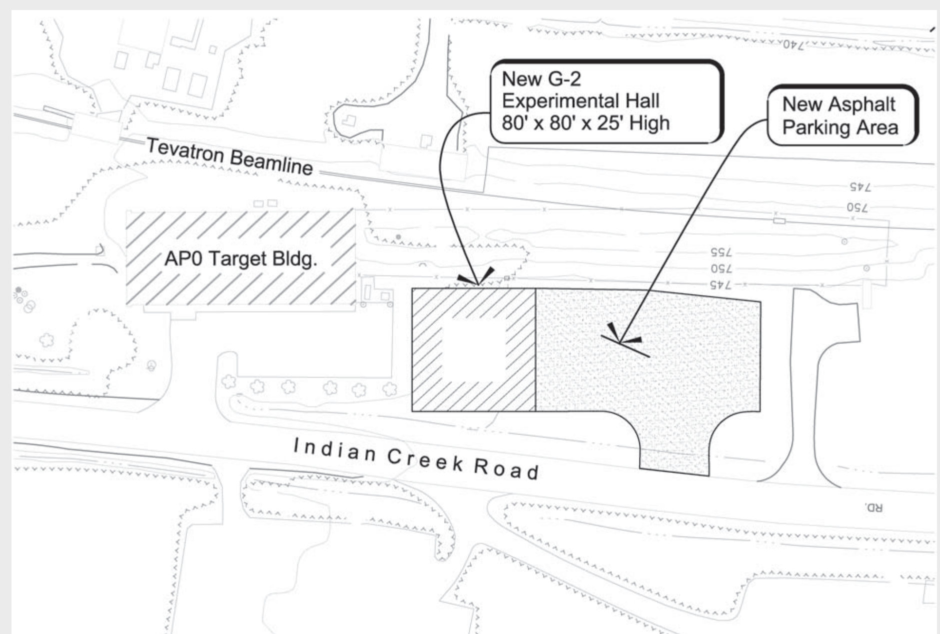


Figure 1 – Location Plan of the New G-2 experimental Hall

- move BNL ring to FNAL
- upgrade RF in Accumulator/Debuncher
- cost and schedule work begun